Green Guide to Composites: an environmental profiling system for composite materials and products

Book

green guide to composites

an environmental profiling system for composite materials and products

BRE

netcomposites

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acknowledgements

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The production and content of this document have been steered by the following organisations, representing a cross-section of the composites industry, and we would like to acknowledge their valuable input and contributions.

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part 1: introduction

Background

Products made from composite materials can offer significant environmental benefits because of their characteristically low weight, good mechanical properties and excellent resistance to corrosion. For example, composites used in cars can reduce the overall weight of the car and so offer fuel savings through the lifetime of the vehicle. However, although the in-service environmental benefits of composites are known, there is far less understanding of the environmental and social implications associated with the manufacture of composite materials and products.

Issues affecting the industry include health and safety, the emission of volatile organic compounds (VOCs), energy consumption and toxicity from manufacture. Alternative materials and technologies (such as closed mould processes, natural fibres and low-styrene resins) have been developed to address these problems, but to date there has still been confusion within the industry as to the detailed benefits of these alternatives.

Purpose and Scope

This guide has been created to enable the composites sector to understand the environmental and social impacts associated with composite production and assist with the decisions made about material and process choice. The materials and processes modelled are rated from A (good) through to E (poor). Twelve different environmental impacts are individually scored and totalled to give an overall environmental impact summary rating. Two social impact ratings are also given.

When measuring environmental impact it is important to consider all the influences through the life of the product. This process is known as Life Cycle Assessment (LCA) and it has been used in this guide for environmental investigation. Because this guide concentrates on materials and manufacturing, as opposed to in-service performance, the impacts associated with products beyond the factory gate (the use, maintenance and disposal stages of the life cycle) have not been assessed.

Within the system boundaries for the LCA, three typical product types have been chosen to reflect a range of different components commonly manufactured using composites:

- A double curvature panel
  – this has a surface area of 1m^2 with a panel stiffness equivalent to a 4mm thick chopped strand mat laminate.
- A flat sandwich panel
  – measuring 1m x 8m with a 25mm thick core, having a panel bending stiffness equivalent to a sandwich panel with a 4mm thick chopped strand mat skin.
- A complex moulded component
  – with a volume of 770cm^3.

Similarly, production processes and materials have been selected to provide a balance between systems that are commonly used across the majority of the composites industry and emerging materials with the potential to provide an environmental benefit. For this reason, materials such as hemp fibre and self-reinforced polypropylene have been included in the guide, but materials that are more specific to a single sector (eg aramid fibre) have not been included.

Within each specific process there are still many processing variations (eg methods for mixing, curing and trimming) in addition to the material choice possibilities. To enable fair comparisons, a base case has been selected for each process. This is used throughout the guide to allow the merits of each process variation to be assessed.

How to Use this Guide

This document is split into five parts:

Part 1 – introduction: The introduction outlines the intent of the guide and gives the overall structure. The life cycle assessment method is introduced along with what has been chosen to be modelled and why.

Part 2 – how this guide was compiled: This section looks in more detail at the life cycle assessment method used in the guide. It outlines which environmental and social factors are being measured and how the ratings are obtained.

Part 3 – production stages: This part of the guide provides background on the social and environmental impacts of the individual stages of production. Guidance then follows on the relative importance of the different production stages, the choices available and the implications of those choices. This part of the guide is designed for situations where a manufacturer is considering just one specific part of the process (eg the mixing stage), as well as to provide greater detail and background information alongside other parts of the guide.

Part 4 – manufacturing processes: This part provides detailed information on the environmental and social impacts of each of the main composite manufacturing processes, showing which stages of each process have the greatest effect. Guidance is also included on process variations that can improve or worsen the environmental impact.

Part 5 – Green Guide ratings: This part contains the A to E Green Guide ratings for a wide range of composite materials and processes, for each of the three product types.

For each product type direct comparisons can be made between different process and material choices.

The Web-Based Guide

This paper based guide provides quick and easy guidance to manufacturers of composites to help them minimise the environmental impact of the products they supply. However, it can only provide basic guidance – the parallel web based guide provides more information and allows users to make more specific or detailed comparisons. The web based guide expands on the information provided in this guide enabling users to compare a far broader range of materials and processes, as well as allowing them to focus in detail on the areas of composite production specific to their own needs.

The web-based guide can be found at:
www.netcomposites.com/composite-tools.asp

BRE Green Guides

BRE use LCA to provide guidance on the environmental impacts of construction products and processes. They have produced a number of tools and publications as part of this work, one of which is the Green Guide to Specification[1], which rates building materials and components on a scale of A to C. This document has been the basis for this new guide on composites.

In common with BRE's other LCA tools and publications, this Green Guide uses the BRE Environmental Profiles Methodology as its LCA approach. An LCA Methodology is a description of the rules that need to be followed to ensure that the LCA is completed fairly and that the results can be used for comparison. The BRE Environmental Profiles Methodology is compliant with a number of ISO standards (ISO 14040 series[2]) which have been developed to standardise and define the manner in which life cycle assessments should be undertaken. The reader should also be aware of ISO standard 14020[3] on Environmental Labels and Declarations.

Further information on the BRE Environmental Profiles Methodology can be found on the BRE website: www.bre.co.uk/envprofiles.

1 The Green Guide to Specification: Third Edition, Jane Anderson, David Shiers and Mike Sinclair, Blackwell Science, Oxford, 2002.
2 BS EN ISO 14040:1997 Environmental Management – Lifecycle Assessment – Principles and Framework.
3 BS EN ISO 14020:2001 Environmental Labels and Declarations – General Principles.

part 2:how this guide was compiled

Life Cycle Assessment (LCA)

The environmental data in this Green Guide to Composites is generated using a technique known as Life Cycle Assessment. LCA is a method of measuring the environmental impacts of a product through its life cycle, often from the cradle to the grave. However, this Green Guide to Composites has studied the life cycle impacts from cradle to factory gate.

In this guide, the LCA has included the impacts associated with the extraction of oil and minerals as precursors to the resin and fibre, the manufacture of the materials, any requirements for transport or packaging and finally the composite manufacturing process itself. It is worth noting that the use of the product, beyond the factory gate, can have a significant effect on the overall environmental impact of the part. However, this guide has been designed only to address the materials and manufacturing processes.

In LCA it is important to ensure fair comparison between different products, and this can only be achieved if the comparison is based on a function that the products are designed to meet. For example, to compare the environmental performance of two products for use as a car bonnet, then each product would first need to meet the bonnet's functional requirements (eg area, strength and stiffness) for the comparison to be valid.

Within this guide therefore, three generic product types have been defined, each with their own criteria, to allow manufacturers to consider environmental data most suited to their particular product. For each of the three products, the amounts of material required and processes necessary have been calculated on the basis of the given criteria so that the results are product specific, and can be used to make comparisons between the impacts of different materials and processes.

Sources of Data

LCA data on the principal raw materials – the polymers, fillers and fibres, have been sourced from internationally recognised databases. Where necessary, this data has been amended or adjusted based on data provided by industrial partners to reflect current UK practice.

For the manufacturing processes, data has been sourced from manufacturers, processors, suppliers or publications. In some instances, it has been necessary to extrapolate data for processes, eg for larger or smaller components, from data provided to the project. In these cases, BRE, NetComposites and the industrial partners have used their best judgement to ensure this gives as accurate a result as possible.

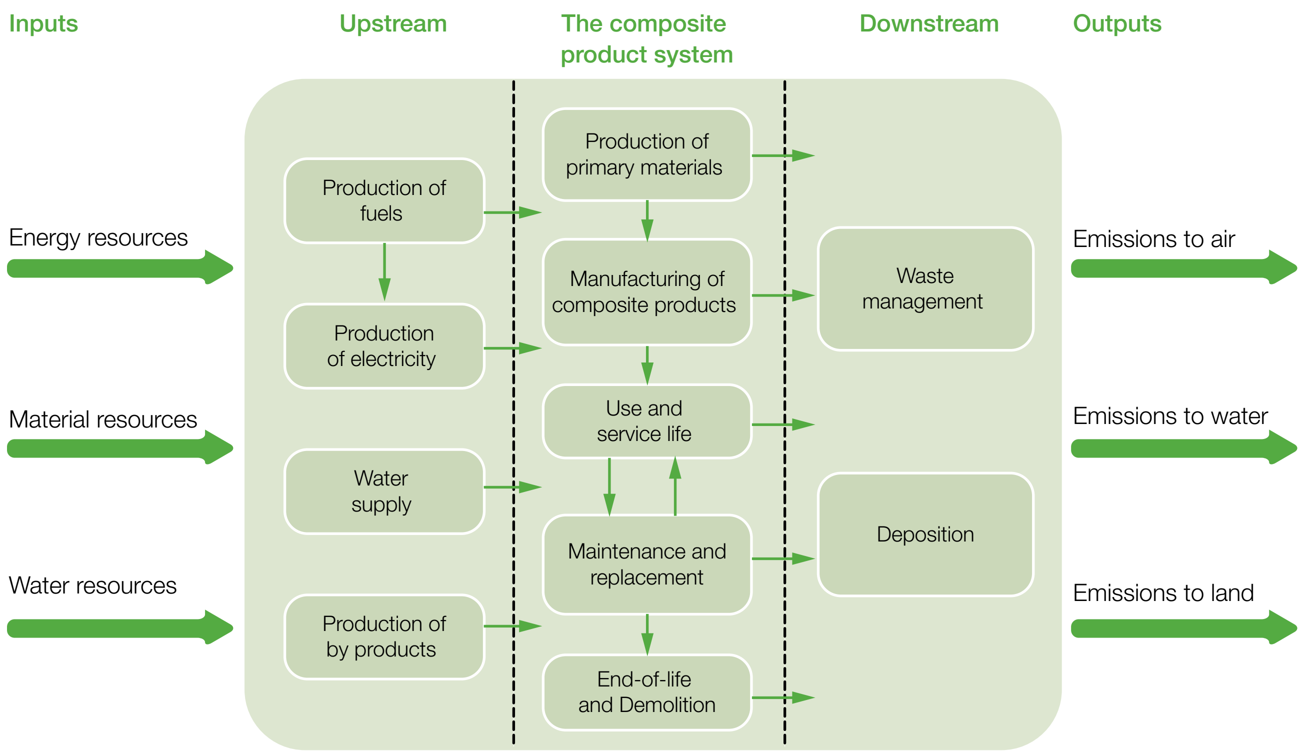


Figure 1: Stages of a composite product life cycle

Environmental Issues

The following environmental issues have been considered within the Green Guide to Composites.

Climate change

Global warming is associated with problems of increased climatic disturbance, rising sea levels, desertification and spread in disease. It has been the subject of major international activity, and methods for measuring it have been presented by the Intergovernmental Panel on Climate Change (IPCC). Gases recognised as having a greenhouse or global warming effect include CFCs, HCFCs, HFCs, methane and carbon dioxide. Their relative global warming potential (GWP) is calculated by comparing their global warming effect after 100 years to the simultaneous emission of the same mass of carbon dioxide.

Fossil fuel depletion

This issue reflects the depletion of the limited resource that fossil fuels represent. It is measured in terms of the primary fossil fuel energy needed for each fuel.

Ozone depletion

Ozone depleting gases cause damage to stratospheric ozone (the ozone layer). There is great uncertainty about the combined effects of different gases in the stratosphere and all chlorinated and brominated compounds that are stable enough to reach the stratosphere can have an effect. CFCs, Halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth's atmosphere, increasing the amount of harmful UVB light reaching the earth's surface.

Human toxicity to air† and human toxicity to water†

The emission of some substances (such as heavy metals) can have impacts on human health. Assessments of toxicity are based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity. Impacts to air and water have been combined in the ratings tables shown in Part 5.

Ecotoxicity†

The emission of some substances such as heavy metals can have impacts on the ecosystem. Assessment of environmental toxicity has been based on maximum tolerable concentrations in water for ecosystems.

Waste disposal

This issue reflects the depletion of landfill capacity, the noise, dust and odour from landfill (and other disposal) sites, the gaseous emissions and leachate pollution from incineration and landfill, the loss of resources from economic use and risk of underground fires etc. Because there is insufficient data available on the fate of materials in landfill or incineration, a proxy figure for these impacts is measured by tonnes of waste produced.

Water extraction

This issue is included because of the value of water as a resource and to reflect the depletion, disruption or pollution of aquifers or disruption or pollution of rivers and their ecosystems due to over extraction.

Acid deposition

Acidic gases such as sulphur dioxide (SO_2) react with water in the atmosphere to form acid rain. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem impairment of varying degrees, depending upon the nature of the landscape ecosystems. Gases that cause acid deposition include hydrogen chloride, hydrogen fluoride, nitrogen oxides and sulphur oxides. Ammonia, a non acidic gas, also plays an important part in the long range transport of the acidic pollutants through the formation of relatively stable particles.

Eutrophication (over-enrichment of water courses)

Nitrates and phosphates are essential for life, but increased concentrations in water can encourage excessive growth of algae, reducing the oxygen within the water. This can lead to increasing mortality of aquatic fauna and flora and to loss of species dependent on low-nutrient environments. Emissions of ammonia, nitrates and phosphates to air or water all have an impact on eutrophication.

Summer smog (low level ozone creation)

In atmospheres containing nitrogen oxides (a common pollutant) and volatile organic compounds (VOCs), ozone creation occurs in the presence of radiation from the sun. Although ozone in the upper part of the atmosphere is essential to prevent ultraviolet light entering the atmosphere, increased ozone in the lower part of the atmosphere is implicated in impacts as diverse as crop damage and increased incidence of asthma and other respiratory complaints.

Minerals extraction

This issue reflects the total quantity of mineral resource extracted. This applies to all minerals, including metal ore, and applies to both UK and overseas extraction. The extraction of minerals in the UK is a high profile environmental topic but the minerals themselves are not considered to be scarce. Instead, this issue is a proxy for levels of local environmental impact from mineral extraction such as dust and noise. It assumes that all mineral extractions are equally disruptive of the local environment.

†Toxicity: It should be noted that issues relating to toxicity generate much debate. Manufacturers are advised to carefully review the material supplier's guidance, to note any relevant regulations, codes and standards appropriate to different industries and materials and to consider the context and application within which the materials are to be used. The results in The Green Guide do consider some toxic effects, but these should in no way be considered comprehensive, for any of the material alternatives considered. Many of the chemicals used in society have not undergone a risk assessment and assessment techniques are still often inconsistent.

Social Issues

Many of the environmental issues detailed above also infer a social impact. Human toxicity and summer smog are perhaps the most obvious in this respect, as by their very nature they have implications to human health. Additionally, mineral extraction and waste disposal have social consequences and can have detrimental effects on local communities.

Alongside these inferred social influences, this guide also directly considers the effect of the working environment on the employee. Whereas the environmental assessment includes the impacts associated with upstream processes such as oil and mineral extraction, materials production and transport, the social assessment concentrates specifically on the composites conversion processes (hand lay-up, press moulding etc) themselves. In assessing the social impact of composite materials and processes, this guide considers the effect of the working environment on the employee in terms of remuneration and exposure to risk.

Exposure to risk

To evaluate the exposure to risk we evaluated the amount of Personal Protective Equipment (PPE) for each of the different processes included within the study, based on typical best working practice. For each stage of each process the level of PPE required was given a numerical value, based on the risk categories in the table below. It is worth noting that some individual manufacturing environments may well have a very different risk profile to the one shown below. For example in large plants where safety helmets may be mandatory, but where the risk is relatively low. However, because the overall score is a summary of the risks to each part of the body, discrepancies in any one risk category do not significantly influence the overall score. This table should not be used as any sort of substitute for rigorous risk assessments of specific processes or environments.

The total scores for the amount of PPE used in each process were transposed into comparative ranking scales running from A to E.

Remuneration

The level of remuneration associated with each manufacturing processes was also studied, based on a limited survey of typical salary levels across different sectors and processes within one region of the UK. These comparative remuneration rates were also broken down into five scales running from A to E, with an A rating indicating the highest remuneration rates for the employee. Because the survey was restricted to one region of the UK to reduce the likelihood of geographical variations, this meant that it was only possible to obtain a limited amount of data on remuneration.

The Green Guide Ratings

When undertaking the studies for this guide, data on impacts from the use of raw materials, energy, manufacturing and emissions associated with the product system under investigation were combined to provide an overall impact in each of the 12 environmental and 2 social impact categories identified above. This approach gives a detailed breakdown of the performance of the product system across the common environmental and social categories.

Within each product type, the results for each issue are then compared. For each issue, there will be a range, with the lowest (minimum) and highest (maximum) impact identified. Figure 2 shows the environmental impacts for sixteen variations plotted on the same axis, running from no environmental impact on the left, to high environmental impact on the right.

A to E ratings are then calculated for each composite product type and issue by assessing where the result lies within the range. An A rating is obtained when the result is within the top 20% of the range with the lowest environmental impact, a B rating when it is within the second 20%, and so on.

In order to ensure that only ‘like with like’ comparisons are made, three separate A to E ranges have been created, one for each product type.

Table showing the risk category ratings for Personal Protective Equipment (PPE)

PPE	Risk categories				
	0*	1	2	3	4
Eye protection	No protection required	Safety glasses	Safety goggles	Face screen and goggles	
Respiratory protection	No protection required	Dust mask	Half mask	Air Stream Full face mask	
Head protection	No protection required				Safety Helmet
Hand protection	No protection required	Work/heat resistant gloves		Cut resistant gloves	
Ear protection	No protection required	Earplugs <90dB		Ear muffs >90dB	
Body protection	No protection required		Disposable suit with hood		

*It was assumed that safety shoes and overalls should be worn at all times

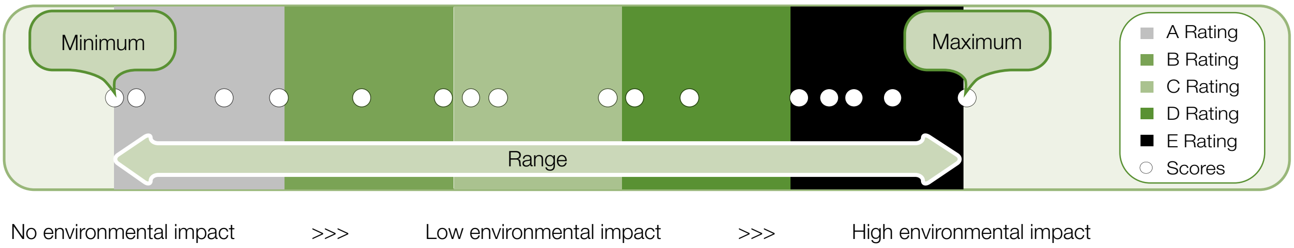


Figure 2: Green Guide environmental rating scale

Environmental Summary Ratings

To assist with using this information, the individual environmental scores are also combined to a single score of environmental performance called a summary rating.

For the environmental summary rating, the different measurement units of each environmental score (eg tonnes of waste) are normalised by dividing them by the impact of one UK citizen. The impact for each issue can then be expressed as a relative proportion of one person's impact for one year.

A second step multiplies this dimensionless data by a weighting factor, the range of those scores is then used to allocate a letter rating of A to E depending on where in the final range each score lies.

The weighting factors were determined from an extensive BRE research programme in 1999 which included consultation with representatives from seven different groups including local and central government, materials producers, construction professionals, environmental activists and lobbyists, academics and researchers.

A surprising degree of consensus was found across the groups regarding the relative importance of different environmental issues, from which it was possible to assign a weighting to the different issues and hence derive the summary ratings. The environmental issues and their relative weightings are:

Climate Change	38.0%
Fossil Fuel Depletion	12.0%
Ozone Depletion	8.2%
Human Toxicity to Air	7.0%
Waste Disposal	6.1%
Water Extraction	5.4%
Acid Deposition	5.1%
Eutrophication	4.3%
Ecotoxicity	4.0%
Summer Smog	3.8%
Minerals Extraction	3.5%
Human Toxicity to Water	2.6%

part 3:production stages

Introduction

Within this guide the process of manufacturing a composite product has been split into a number of different stages. This part of the guide is designed to provide information on the environmental and social impacts of each manufacturing stage, as well as the choices that exist within them.

Figure 3 shows the stages of composite product manufacture within the framework of life cycle assessment. Energy, material and water resources are used in creating the product, whilst the associated process has resultant emissions to air, land and water.

Each stage of the manufacturing process has an environmental impact that contributes to the total impact for that composite product, and there may be a number of choices for each manufacturing stage.

These impacts of each manufacturing stage vary in their magnitude and range, and to select the best environmental option it is necessary to see which parts of the process contribute the most to the overall total.

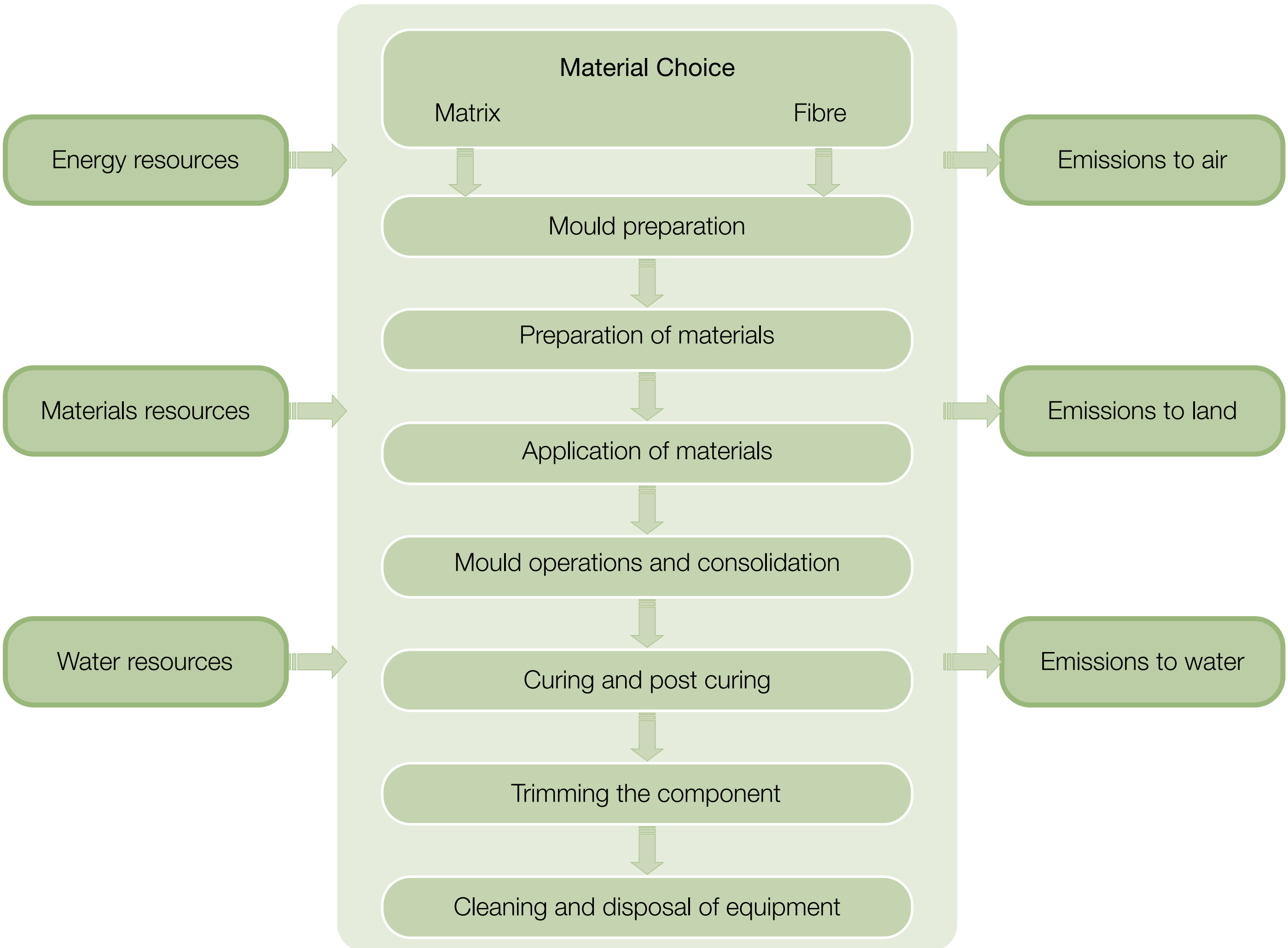


Figure 3: Generic illustration of composite product manufacture

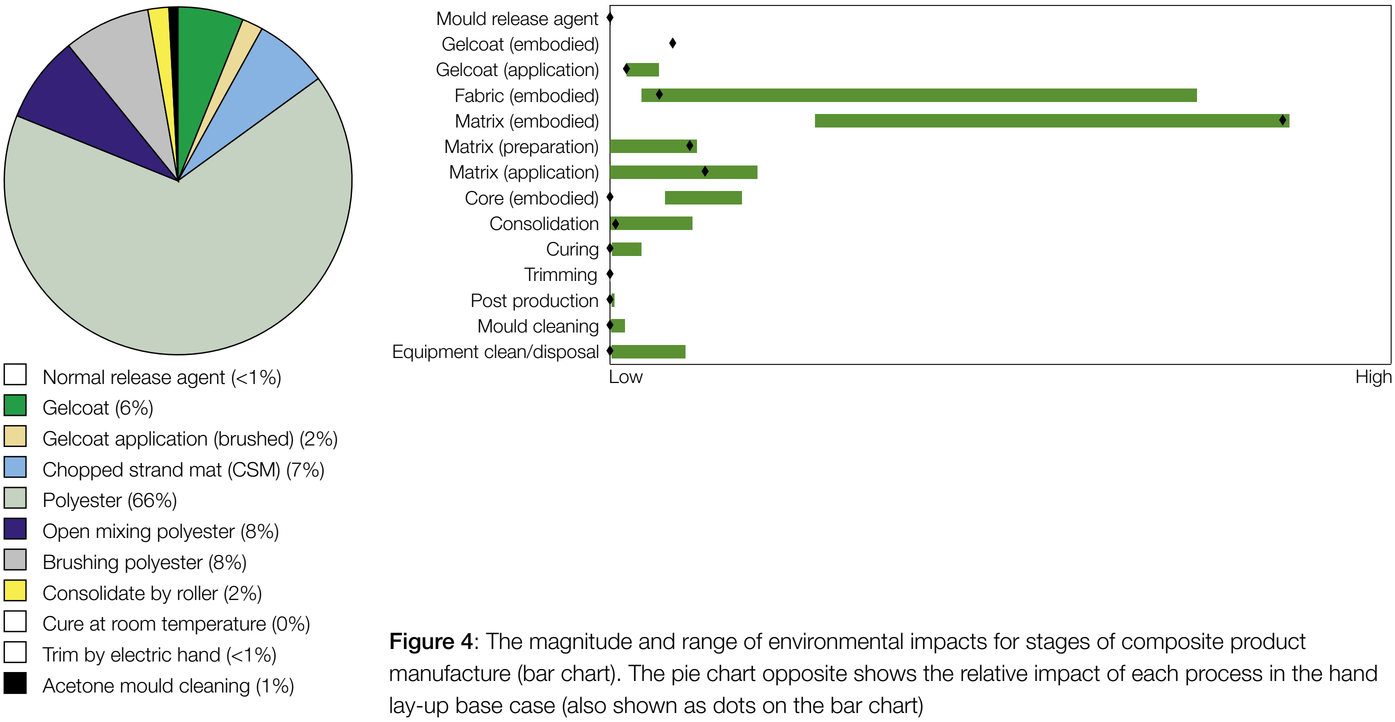


Figure 4: The magnitude and range of environmental impacts for stages of composite product manufacture (bar chart). The pie chart opposite shows the relative impact of each process in the hand lay-up base case (also shown as dots on the bar chart)

The bar chart in Figure 4 shows the range of possible impacts within each manufacturing stage, for all the possible material and process options evaluated. The impacts for a single process (the hand lay-up base case) are shown as black dots and the relative impact of each stage for this product is shown in the pie chart.

In Figure 4 the bars refer to the range of possible values of environmental performance. The lower boundary of each range is the lowest possible impact where this stage of composite manufacture is applied and if the stage is not applied (eg where no gelcoat is used) then the impact for that stage is zero.

Figure 4 shows that the embodied impacts of the materials have the largest environmental impact. However, depending on the composite process, many of the other stages can contribute a sizeable proportion of the total environmental impact. Not all of the choices within process stages are mutually exclusive and the choice of one may affect the magnitude and range of impacts of another.

This co-dependency is most evident within the choice of process, fibre and matrix. For instance, if a fibre of low environmental impact is chosen, it may not then be possible to choose the matrix with the lowest environmental impact. These choices also determine the amount of material needed for manufacture, where material quantity has a significant influence on the overall impact.

In this guide we have studied a selection of matrices, fibres and pre-impregnated fibre combinations. These materials have an inherent embodied environmental impact that arises from the extraction of raw materials and the refining of those materials into products such as matrices and fibres. The upstream embodied environmental impacts are discussed in the material choice subsections that follow.

In addition to the embodied environmental impact of these materials, there are also further process related impacts arising from their use in the factory. These impacts are discussed in the process choice subsections that follow. Beyond the factory gate, the impacts associated with composite product manufacture become a part of the embodied impact of the finished composite product.

Guidance now follows on each stage individually, where issues of co-dependency are reviewed where applicable.

Material Choice: Matrix Materials

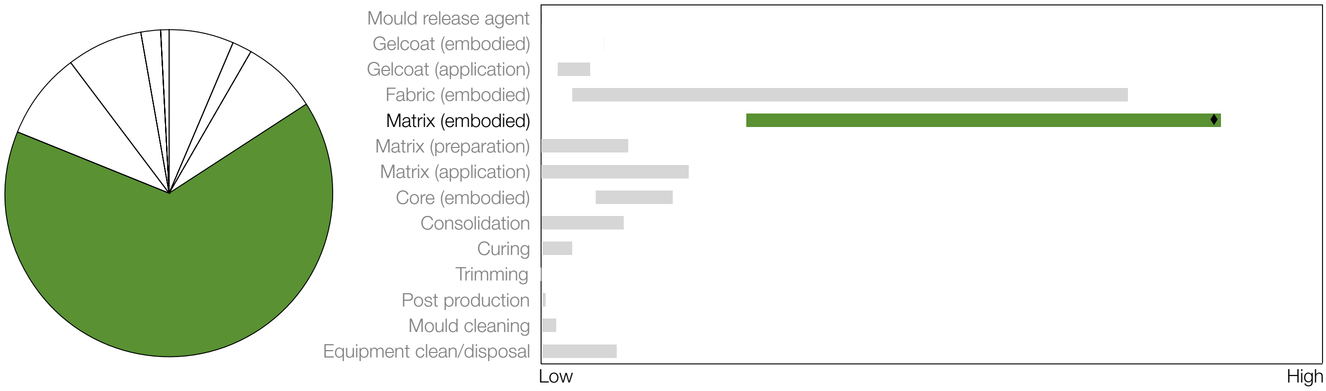


Figure 5: Pie and bar chart showing the relative impact and range of impacts of the matrix, the dot and pie chart representing the impact of matrix in the hand lay-up base case

The matrix is made up of a polymer and often other components such as catalyst, accelerator and filler. The polymers are based on fossil fuels, and have considerable environmental impact associated with their raw materials extraction, processing and manufacture. Due to the high proportion of the matrix and its inherent environmental properties, in most cases it will be the greatest cause of environmental impact for the composite product. A description of the matrix materials studied is given below.

Base Polymers

From the range of polymers used in composite products, this study has focused on three main types:

- Polyester resins
- Epoxy resin
- Polypropylene

Catalysts and Accelerators

Various catalysts and accelerators are used within composite manufacture, such as MEKP and cobalt napthenate. Although these are used in very small quantities and hence do not directly affect the environmental impact of the resin, their use does affect cure time and temperature and, where they can reduce the use of ovens or autoclaves, they can bring a beneficial environmental contribution.

Fillers

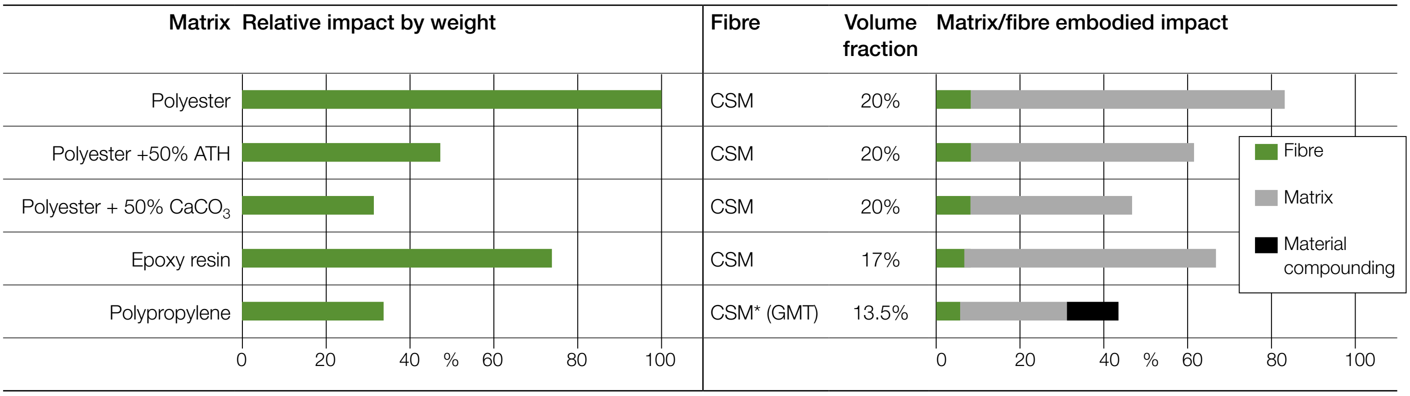
Fillers are normally mineral based with much smaller processing and manufacturing impacts than the base polymers. Because the filler replaces some of the polymer within the matrix, there can be considerable environmental advantage to their use. Two fillers have been modelled in this study:

Alumina Trihydrate (ATH) ATH is an intermediary product of the production of aluminium from bauxite and is used as a fire retardant additive. The environmental impacts are associated with mineral extraction and processing energy.

Calcium Carbonate ($CaCO_3$) Calcium carbonate is usually used to reduce the amount of resin used whilst offering a small increase in stiffness. Environmental impacts associated with calcium carbonate production are primarily related to mineral consumption.

Embodied Environmental Impacts

Figure 5 indicates clearly that the matrix usually has the greatest individual impact in the composite process. The polyester in the hand lay-up base case represents 65% of the final impact and is the matrix with the greatest environmental impact of all those modelled in the guide. This impact can however be reduced by choosing alternative matrices.



* CSM – Chopped glass strands

Figure 6: The relative impact of matrices by weight alongside the relative** embodied impacts of the matrices and fibres needed to make the 1m^2 double curvature panel
** relative to all matrix/fibre combinations in Figures 6, 8, 9 and 10.

For direct comparison, the environmental impact of each matrix by weight is shown in Figure 6. Because different quantities of each of the different matrices are required to make a component with the same structural performance, a second bar chart is shown alongside which compares the embodied environmental impact of the matrix and fibre required to make the 1m^2 double curvature panel. All the matrix/fibre embodied impact bar charts in this section (Figures 6, 8, 9 and 10) are on the same scale to allow direct comparisons between the results in each chart.

From Figure 6 it can be seen that, by weight, polypropylene has the lowest environmental impact with unfilled polyester having the highest. Epoxy resin has a lower impact than polyester, but using calcium carbonate filler halves the impact of polyester simply by reducing the amount of resin used.

Low styrene polyesters are not shown on this graph because they have comparable embodied impacts to normal polyesters. They do however offer an environmental benefit in the mixing and application stages discussed later.

In the matrix/fibre embodied impact assessment, the fibre – modelled as a random glass mat – has been kept constant and different resin types have been investigated. For GMT, the impact of the GMT compounding process is included as it is part of its embodied impact and ensures the comparison is fair. The results show a similar trend to that seen in the comparison of matrix materials by weight.

Recommendation: When using polyester, the inclusion of fillers greatly reduces the environmental impact, with calcium carbonate having a lower environmental impact than ATH. Polypropylene has a lower impact on the environment than the epoxy and polyester resins.

Material Choice: Fibres

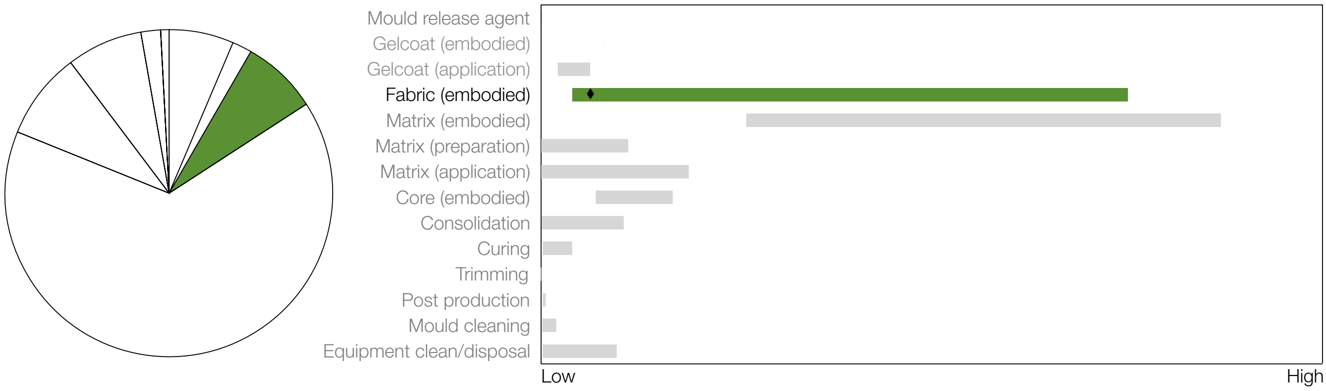


Figure 7: Pie and bar chart showing the relative impact and range of impacts of fibres, the dot and pie chart representing the impact of the fibre in the hand lay-up base case

This guide has reviewed four reinforcement fibres, including glass, carbon, hemp and polypropylene.

Glass

Glass is used in a number of different forms, including rovings, woven fabrics, chopped strand mat and chopped fibres. Environmental differences occur mainly due to the differing energy requirements between the methods of producing the different fibre forms.

Carbon

Carbon fibre has a relatively high environmental impact, closely linked to energy demand during its manufacture. However, for the same structural performance less carbon fibre is needed in a composite product when compared with other fibre types, so its comparative environmental impact is reduced.

Hemp

Hemp fibre is a natural reinforcement manufactured from an agricultural crop. Whilst there are some impacts that arise from its cultivation, the energy demand is very low which results in a relatively low environmental impact.

Polypropylene

The constituent materials are a particularly significant part of the environmental impact of polypropylene, and polypropylene fibres have a higher environmental impact than glass and hemp. Whilst a combination of polypropylene fibres in a polypropylene matrix can result in a fully recyclable composite, this has not been assessed in this guide.

Embodied Environmental Impacts

Figure 7 shows the range of impacts of the fibre, as well as the position of the impact of the glass fibres in the hand lay-up base case. It can be seen that the impact of the glass CSM is only 7% of the total, but that other fibres and fabric forms can have a greater impact. From Figure 8 it can be seen that, by weight, hemp performs better than glass CSM, woven glass, glass rovings and woven polypropylene. Woven carbon has the highest impact by far.

In the matrix/fibre embodied impacts comparison, each fibre is combined with polyester resin. Although hemp performs best by weight, woven glass actually performs better in a panel with equivalent properties as it requires less material. Woven carbon, having even higher structural qualities, requires the least amount of matrix but still has the highest impact.

The choice of process, and hence volume fraction, can also have an impact on the final assessment, and Figure 9 shows identical materials being used in hand lay-up and RTM processes. The inherent nature of the RTM process means that a higher fibre volume fraction is possible, resulting in lower resin usage and better environmental performance when compared to hand lay-up.

Recommendation: Significant differences exist between the carbon, glass, polypropylene and hemp fibres. Be aware however that it is often the amount of matrix that is combined with the fibre that determines the final impact. Carbon has an inherently high environmental impact, though this is often offset by its superior mechanical properties.

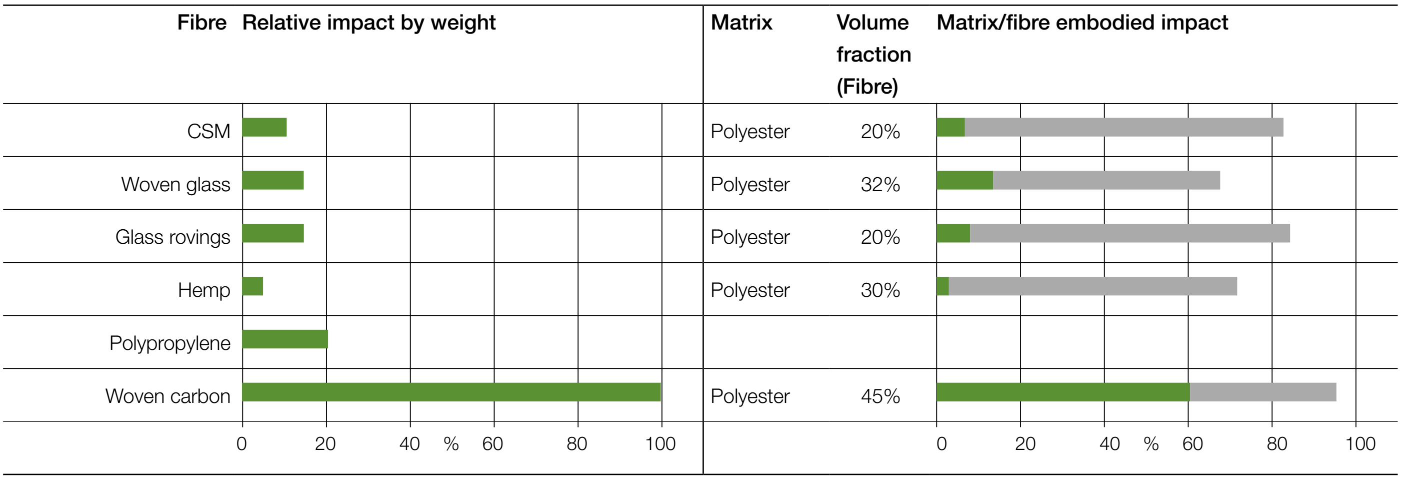


Figure 8: The relative impact of fibres by weight alongside the relative embodied impacts of the matrices and fibres needed to make the 1m^2 double curvature panel

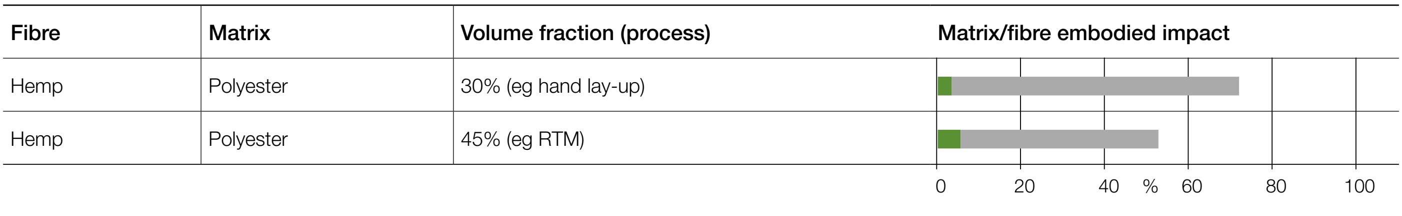


Figure 9: The final embodied impacts of materials used for hand lay-up and RTM processes using identical materials

Material Choice: Pre-impregnated Materials

For many composites manufacturing processes the fibre and matrix are already combined into a pre-impregnated material. These materials can offer environmental impact reductions as well as providing a cleaner and safer working environment, and several pre-impregnated materials have been included in this guide:

- Co-mingled glass and polypropylene fibres (Twintex)
- LFT – Long fibre thermoplastic: glass fibre and polypropylene
- GMT – Glass mat thermoplastic: glass fibre and polypropylene
- PP/PP – polypropylene fibre/tape and polypropylene
- SMC – Sheet moulding compound: glass fibre and polyester
- Glass/Epoxy Prepreg
- Carbon/Epoxy Prepreg

The results in Figure 10 can be directly compared with previous charts, showing that glass/polypropylene pre-impregnated materials have the lowest environmental impacts of all the resin and fibre combinations. The polyester based pre-impregnated materials have some of the highest embodied impacts, although the overall process impacts can be very low due to the processes that utilise these materials. The carbon/epoxy prepreg has the highest embodied environmental impact for the 1m^2 double curvature panel, although this embodied environmental impact reduces in comparison to other combinations of matrix and fibre in applications where the relatively high strength of the carbon can be fully utilised.

Recommendation: In general, pre-impregnated materials and associated processes offer good environmental performance over more traditional composite materials and manufacturing processes.

Pre-impregnated materials	Volume fraction
Co-mingled glass/polypropylene	60%
LFT (Glass/polypropylene)	19%
GMT (Glass/polypropylene)	13.5%
PP/PP	6%
SMC (Glass/polyester)	19%
Glass/epoxy prepreg	55%
Carbon/epoxy prepreg	60%

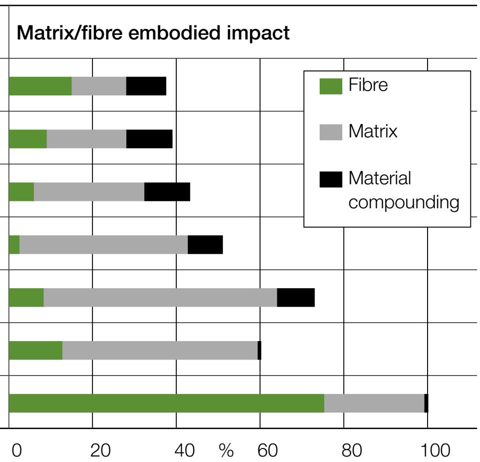


Figure 10: The relative embodied impacts of the pre-impregnated materials needed to make the 1m^2 double curvature panel

Material Choice: Core Materials

Figure 11: Pie and bar chart showing the relative impact and range of impacts of the core (pie chart here is for the 1m x 8m component with a PVC core using hand lay-up base case conditions)

The most common core materials are low in density, so they can help achieve an increase in panel stiffness for only a very small weight penalty. Investigations have looked at PVC and balsa core alternatives.

The findings of the core study are displayed in Figures 11 and 12. The PVC option is found to have a higher environmental impact than the balsa core by some 60%, due to the inherent differences in the sources of the two materials. Balsa is a wood product with fairly low impacts associated with plantation and milling activity, whilst PVC has quite a high impact arising from the refining processes necessary to extract the material from petroleum sources.

Recommendation: Study findings conclude that environmental saving can be achieved through core choice. The balsa timber core is found to give improved environmental performance compared to a PVC core.

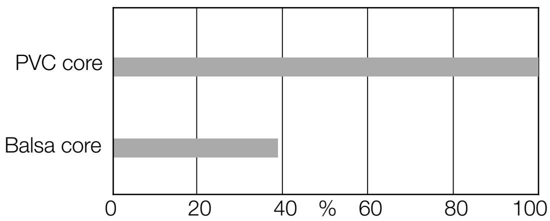


Figure 12: The relative impacts of different core options

Process Choice: Gelcoats

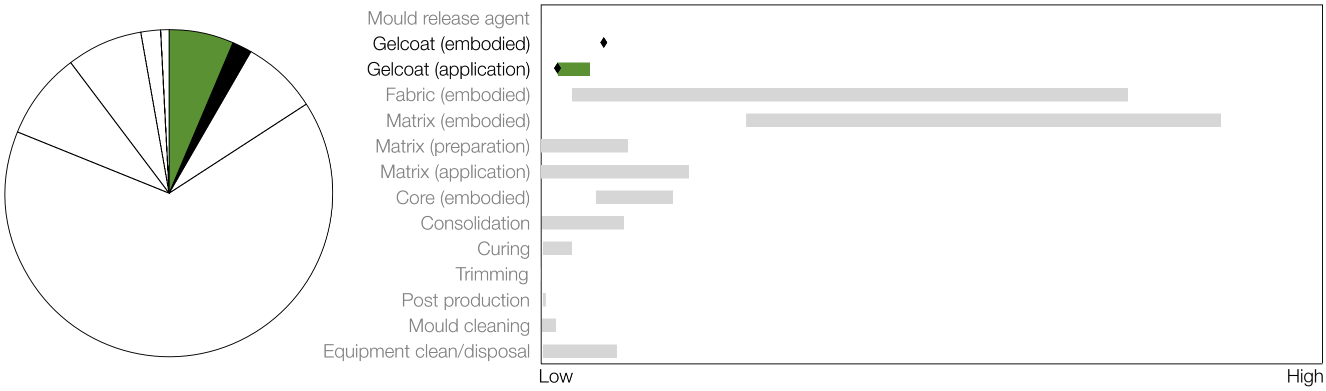


Figure 13: Pie and bar chart showing the relative impact and range of impacts of using gelcoats. Embodied impact of the gelcoat (green) and impact arising from its application (black) are shown on the pie chart for the hand lay-up base case

Gelcoats are often used in composite manufacture to provide a good surface finish to the component. The gelcoat is resin based, often with a filler, and can be applied by brush, roller or spray. From Figure 13 it can be seen that most of the impact is due to the material itself rather than its application.

The impact due to method of application varies due to the difference in emissions given off in each process. Impact variations can be seen in Figure 14 and show that most impact arises from uncontrolled spraying and the least from brushing.

Open mixing of gelcoat formulations can pose a risk to the operator if not handled correctly, or if the correct levels of PPE are not utilised, potentially including respiratory, eye and skin protection. When closed mixing is employed the level of risk may be reduced. The application of gelcoats poses additional risks, such as from spraying and splashing.

Although there have been recent technical developments in the production of low VOC gelcoat systems, due to the developments becoming commercially available after the assessment of materials, these have not been assessed within this guide. Whilst it could be assumed that these systems may have a lower environmental impact, no assessment of these systems has been made.

Recommendation: Minimise impact from emissions by brushing the gelcoat. Uncontrolled spraying increases the impact by a factor of three.

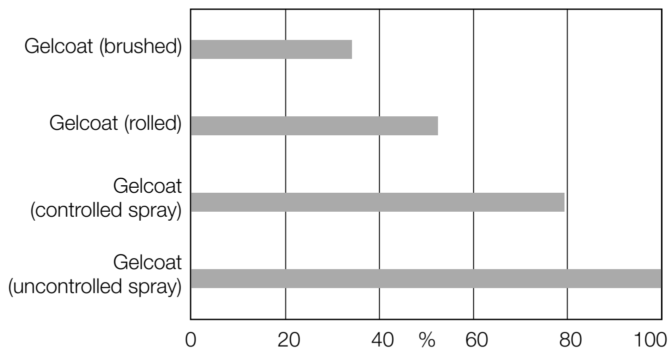


Figure 14: Comparison of environmental impacts of gelcoat application techniques

Process Choice: Material Preparation

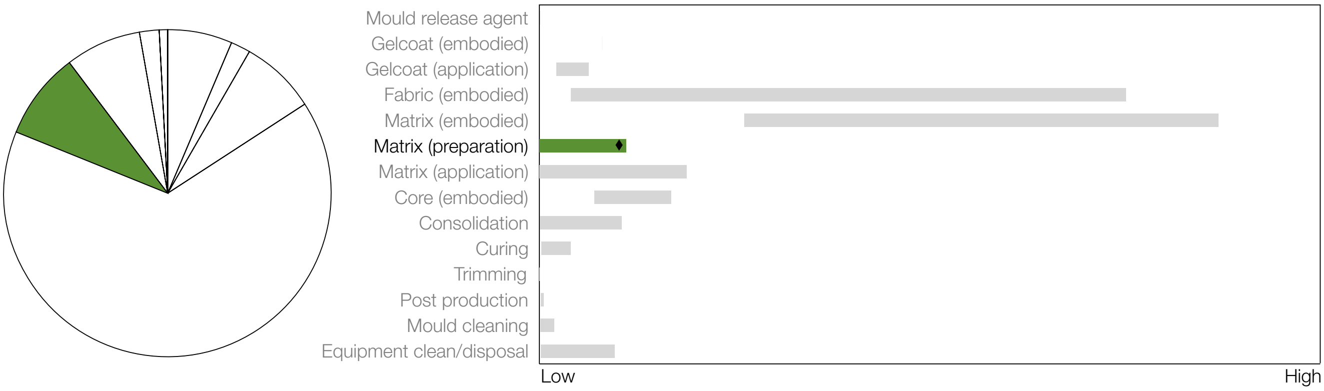


Figure 15: Pie and bar chart showing the relative impact and range of impacts of matrix preparation. The pie chart and dot represent the impact of polyester preparation in the hand lay-up base case

This stage in composite product manufacture involves the preparation of both the matrix and fibre, including resin mixing and cutting of the fibres and fabrics.

Resin Preparation

Emissions from the styrene used in polyester resins are a significant source of impact during both the mixing and application of a resin. Epoxy and polypropylene do not contain styrene, so there are no significant impacts associated with the mixing of these resins.

Figure 15 shows the impact of open mixing of the polyester resin in the hand lay-up base case and represents 8% of the total impact. Figure 16 shows the comparative impacts of the open mixing of four polyester resins alongside that of closed mixing. The chart shows that the evaporation of styrene during resin preparation can most effectively be avoided through the use of closed mixing, although the use of low styrene polyester resins can reduce the emissions by 50%. The use of filler also provides a reduction in emissions.

Open mixing of resin systems can pose a risk to the operator if not handled correctly, or if the correct levels of PPE are not utilised, potentially including respiratory, eye and skin protection. When closed mixing is employed the level of risk may be reduced.

Recommendation: Resin preparation has a notable contribution to overall environmental impact, and significant environmental improvement can be achieved through closed mixing. If this is not feasible then a low styrene resin or a resin containing a filler will give lower emissions from mixing.

Fibre/Pre-impregnated Material Preparation

The main options available for the preparation of fibres and pre-impregnated materials are either to cut by hand or by machine. The machine that has been modelled minimises waste by nesting the cut shapes, and it was assumed that this gave a 20% reduction in the quantity of waste material. For materials with a large environmental impact, such as carbon/epoxy, savings can be made by using machine cutting. For materials of low environmental impact, such as hemp, the waste savings made by machine cutting are offset by the power usage of the machine, so there is no overall reduction in environmental impact. However, the effect of fibre preparation on the overall product environmental impact was found to be less than 1% for all the materials studied.

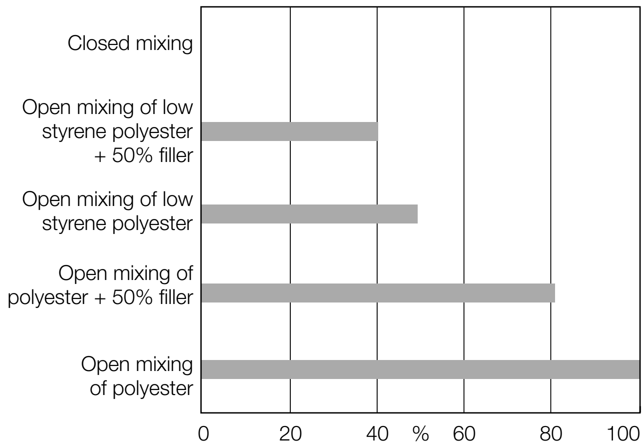


Figure 16: Comparison of open and closed resin mixing of polyester resins

The preparation and application of pre-impregnated materials does not generally carry a significant level of risk to personnel, although there is some risk due to temperature in handling hot thermoplastic compounds and due to cutting and handling prepreg and SMC materials.

Process Choice: Matrix Application

Figure 17: Pie and bar chart showing the relative impact and range of impacts of resin application. The pie chart and dot represent the impact of application by brush in the hand lay-up base case

The application of the matrix can have a large environmental impact, mainly due to associated styrene emissions. Impact potential is therefore directly linked to both resin type and application process.

The impacts from applying an unfilled polyester matrix, using a range of methods, are presented in Figure 18. Applying with an uncontrolled spray has the greatest impact, but this can be reduced with controlled spraying. The brushing technique used in hand lay-up and vacuum bagging produces fewer emissions but also includes impacts from the use of acetone for cleaning the brushes. The overall impact however is lower than both of the spraying techniques. The pultrusion method involves larger emissions than brushing due to the large surface area of the resin bath, but again less than for the spraying techniques. Whilst resin injection pultrusion systems may have a lower environmental impact, no assessment of this form of pultrusion has been made.

Closed moulding techniques such as RTM and resin infusion do not create emissions but do incur an energy impact from the injecting and infusing of the matrix. Autoclave and compression moulding use pre-impregnated materials and so have no resin application impact.

The choice of resin also affects the impact of this process stage and Figure 19 shows the variation in impact from brushing different matrices. The same trends can be observed as with resin preparation, with the use of a low styrene resin and using fillers reducing impact considerably. Even though there are no significant impacts in terms of emissions from epoxy resin, there are still impacts from cleaning of the brushes and these impacts occur regardless of which resin is used.

When applying resins by brushing or spraying there are a number of risks to the operator that can be minimised through the use of PPE, such as masks, goggles, disposable suits and gloves. In closed moulding processes, the risk to personnel is greatly reduced.

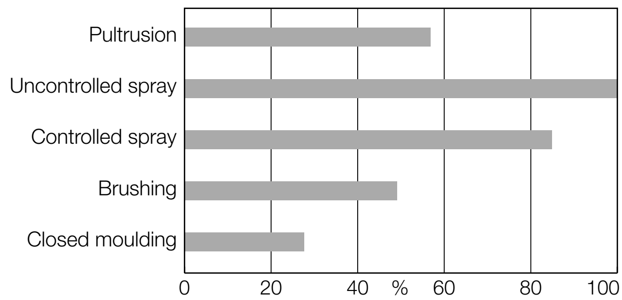


Figure 18: Comparison of impacts from applying polyester resin using a variety of techniques

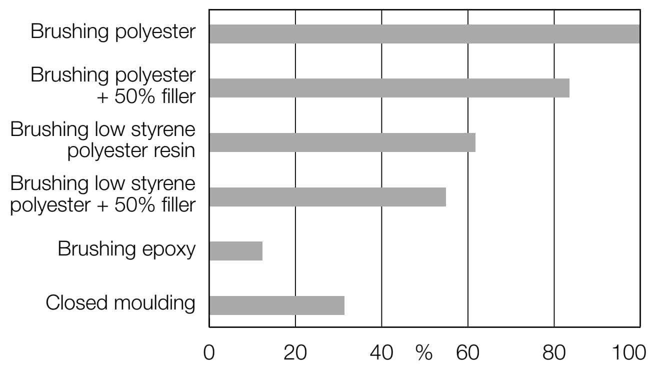


Figure 19: Comparison of impacts from applying different resins by brush

Recommendation: To minimise the environmental impact of material application, closed mould techniques or methods such as autoclave or compression moulding should be used. If an open mould technique or pultrusion is being utilised, then minimizing the styrene content of the resin will reduce the environmental impact. This can be done by using epoxy or a low styrene or filled polyester system, where suitable. With spray-up, using a controlled spray rather than an uncontrolled spray will have a considerable environmental advantage.

Process Choice: Mould Operation and Consolidation

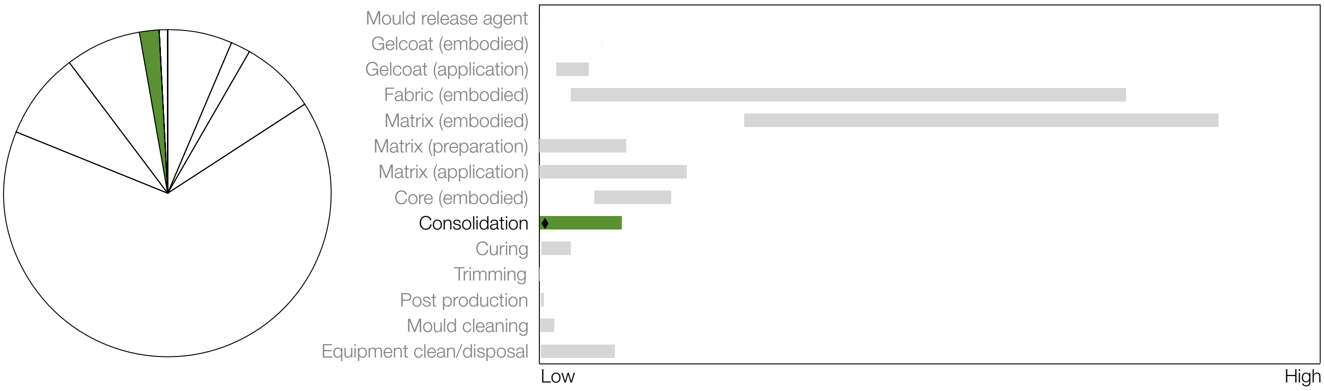


Figure 20: Pie and bar chart showing the relative impact and range of impacts of mould operation and consolidation. The pie chart and dot represent the impact of consolidation by roller in the hand lay-up base case

In the hand lay-up base case example there is an impact due to the acetone needed to clean the roller. In vacuum bagging, the consolidation process impact is purely the power used to create the vacuum, although in RTM and press moulding the consolidation impact is significant and can contribute around 10% of the total impact.

Recommendation: The method of consolidation and its environmental impact is determined solely by the choice of process so it is difficult to achieve improvement. The impacts however can be significant and so potentially could influence process choice.

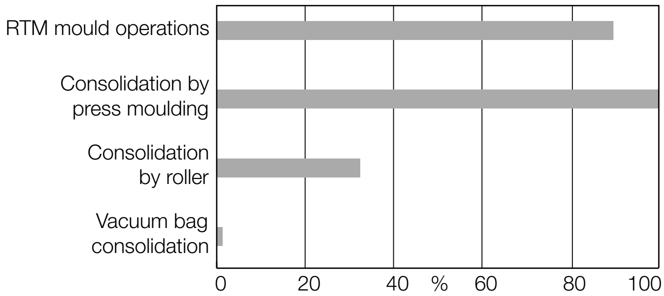


Figure 21: The relative impacts of the consolidation stage

Process Choice: Equipment Environmental Impacts

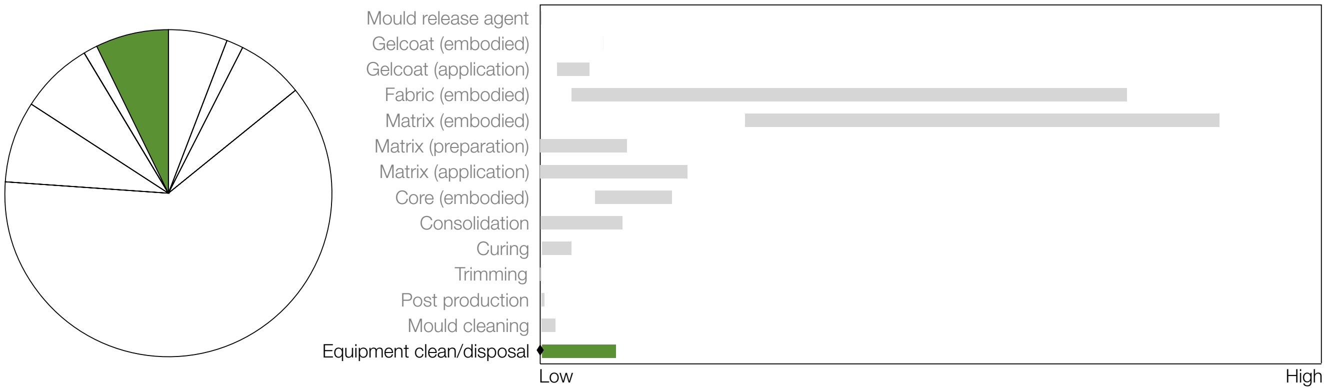


Figure 22: Pie and bar chart showing the relative impact and range of impacts of equipment use. The pie chart and dot represent the impact of the use of a vacuum bag in the vacuum bagging base case

This section details the impacts from the equipment used in composite manufacture. The embodied impacts that arise from capital equipment such as moulds, RTM equipment, compression presses and pultruders have been ignored as is the norm in LCA studies. This can also be done on the basis that their embodied impact is small given their long life.

The only elements of equipment that have a large environmental impact are the consumables used in the vacuum bagging which are disposed of after each moulding. The impact of the materials and disposal of the vacuum bag is 10% of the basic vacuum bagging process. A significant but much smaller impact results from the use and disposal of the pipes used in resin infusion moulding, contributing 2% of the total basic resin infusion process impact.

Low Impact Process Stages

Figure 23: The relative impact and range of impacts for the remaining stages of composite product manufacture

From Figure 23 it can be seen that the remaining stages of the manufacturing process have very little impact. For these stages only brief recommendations will be given:

Mould Preparation

A conventional release agent and an eco-release agent were studied and, for both, the embodied impact of the release agent was found to contribute less than 1% to the overall impact of the process. The recommendation for mould preparation is therefore to choose the type and amount of release agent on the basis of performance in terms of minimising scrap components, as this will have a greater environmental impact than the embodied impact of the mould release itself.

Some mould preparation systems pose a small level of risk to personnel, which can be controlled through the use of PPE such as goggles, gloves and respiratory protection.

Curing and Post Curing

Curing in ovens, autoclaves, heated moulds and heated dies were all modelled and in all cases apart from one, the impact was found to be less than 1% of the overall impact. Within the materials studied, the exception to this is SMC compression moulding, where heated moulds cause a large energy impact. Although they have not been studied, this may also be true of other polyester moulding compounds such as DMC or BMC. Additionally, if inefficient ovens, autoclaves or mould heating techniques are used, or if they are not fully loaded, the environmental impacts from curing and post curing can become significant. There may be some risk to the operator from the emission of VOCs during the curing process, which can be controlled through the use of respiratory protection if necessary.

Trimming

The overall influence of trimming on the environmental impact of a composite component is minimal, so no recommendation is given. Manual trimming systems may pose more risk to the operator than automated systems, through exposure to dust and cutting tools.

Cleaning

Acetone and a butanone/toluene based cleaning agent were studied and both were found to have impacts of less than 2%. In the case of RTM system cleaning, where acetone is used to clean away the residual polyester resin, the cleaning of the machine contributes less than 1% of total basic RTM process impact.

The same finding applied to cleaning of pultrusion equipment with acetone and glycol ether, where again the impact was less than 1% of the total basic pultrusion process. Hence, the recommendation is to choose the type and amount of cleaning agent on the basis of performance in terms of minimising scrap components and increasing mould longevity, as this is likely to have more environmental impact than the embodied impact of the cleaning agent.

Where acetone is regularly used for cleaning moulds and ancillary equipment it is advisable that an acetone recycling unit is used to give both environmental and economic benefits. Throughout this guide we have assumed that, after evaporation during the cleaning process, recycling is used to recover 75% of the remaining contaminated acetone.

Some mould cleaning systems pose a small level of risk to personnel, which can be controlled through the use of PPE such as goggles, gloves and respiratory protection.

part 4: manufacturing processes

Introduction

This part of the guide summarises and prioritises the key environmental issues facing each of the eight common manufacturing processes reviewed by the guide. Whilst it is recognised that the choice of manufacturing process will primarily be influenced by economic and design factors, this guide only considers environmental and social impacts.

The following processes have been assessed within the guide.

- Hand Lay-Up
- Spray-up
- Vacuum Bag Moulding
- Resin Infusion
- Resin Transfer Moulding
- Autoclave Moulding
- Pultrusion
- Compression Moulding

For each process a base case has been chosen, defined as the most common way of performing that process with the most common materials. This provides a benchmark against which changes in material or process technique can be measured.

Trends and recommendations from Part 3 are summarised for each process, with process variations being highlighted as significant if they change the overall impact of the process by more than 1%. Variations are given for the 1m^2 double curvature panel except where the trends are different for the other components.

Details of each base case are included in the assessment of each process, together with a pie chart to show the relative environmental importance of the materials and production stages.

It is important to note that the pie charts illustrate the relative importance of each choice in the base case, and that different choices (eg a different resin) will change their relative impact.

Hand Lay-Up

In hand lay-up, fibres are impregnated with resin by hand using brushes and rollers. The resultant composite is cured at atmospheric pressure, either at room temperature or in an oven. This process can be used to make the 1m² double curvature panel and the 1m x 8m sandwich panel case studies.

Figure 24 shows that the largest environmental impact from the hand lay-up process arises from the resin. The majority of this derives from the embodied up-stream impacts of the raw material, followed by the impacts from emissions during the mixing and application of the resin. The embodied up-stream impacts of the fibre and gelcoat are also significant.

All of the options listed in the table below were evaluated and it was found that variations in curing, cleaning and trimming operations had no significant effect on the total environmental impact.

The largest improvement in environmental performance can be achieved through changing the resin and fibre, using a closed technique to mix polyester resins and applying the gelcoat by brush. Compared to unfilled polyester, epoxy gives an improvement of 30%, low styrene polyester an improvement of 7% and 50% $CaCO_3$ filled polyester an improvements of 33%. This is due in part to reductions in the embodied impacts and in part to reductions in emissions.

Changing the fibre from CSM to hemp gives an improvement of 12%, whilst changing to woven glass gives an improvement of 18% (when using unfilled polyester). An improvement of 9% can be made if closed mixing is employed and a deterioration of 3% is incurred when the gelcoat is sprayed (uncontrolled) instead of being brushed. An overall improvement of 48% can be made on the base case when using woven glass, 50% $CaCO_3$ filler, low styrene polyester and closed mixing.

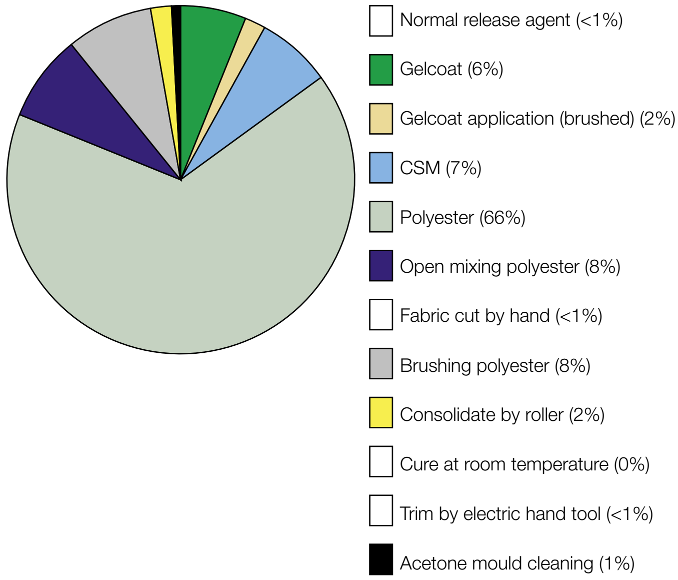


Figure 24: Breakdown of impacts for the basic hand lay-up process for making the 1m² double curvature component

Hand Lay-Up	
Base case process	**Other options modelled**
Polyester Resin (80% volume fraction)	Low styrene polyester resin Epoxy resin
No filler	15%, 30% and 50% ATH filler 15%, 30% and 50% $CaCO_3$ filler
Chopped strand mat (20% volume fraction)	Woven glass mat Hemp (with polyester resin)
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Normal mould release	Eco mould release
Gelcoat	No gelcoat
Gelcoat applied by brush	Rolled gelcoat Sprayed gelcoat (controlled and uncontrolled)
Open mixing of resin	Closed mixing of resin
Fabric cut by hand	Mechanically cut fabric
Resin applied by brush	
Roller consolidation	
Room temperature cure	Oven cure
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent

Spray-Up

The spray-up process incorporates chopped glass rovings with catalysed resin and sprays the resultant mix onto the mould surface, with further compaction using rollers if required. Curing is either at room temperature or in an oven, and this process can be used to make the 1m² double curvature panel and the 1m x 8m sandwich panel case studies.

As with hand lay-up, the resin is the largest contributor to the total environmental impact of the composite. In spray-up, closed mixing of the resin ensures that there are no emissions at this stage, but the spraying process creates large quantities of airborne styrene and hence the emissions during application are very high.

The overall impact can be reduced by 6% by using a controlled spraying technique, 6% by using a low styrene resin and 31% by using 50% $CaCO_3$ filler. An improvement of 1% can be achieved by controlled spraying of the gelcoat and 3% by brushing.

The impacts from curing, mould cleaning and trimming all have little significance on the overall environmental performance and no marked improvement can be achieved by varying these options.

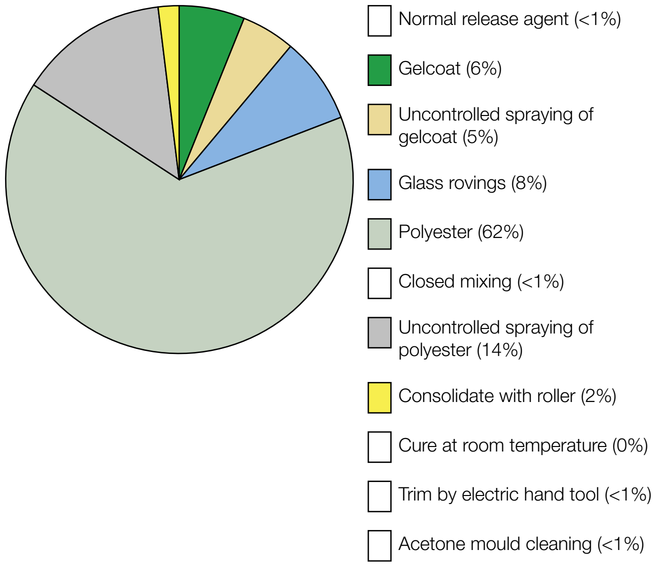


Figure 25: Breakdown of impacts for the basic spray-up process for making the 1m² double curvature component

Spray-Up	
Base case process	**Other options modelled**
Polyester Resin (80% volume fraction)	Low styrene polyester resin
No filler	15%, 30% and 50% ATH filler 15%, 30% and 50% $CaCO_3$ filler
Chopped Glass Rovings (20% volume fraction)	
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Normal mould release	Eco mould release
Gelcoat	No gelcoat
Sprayed gelcoat (uncontrolled)	Brushed gelcoat Rolled gelcoat Sprayed gelcoat (controlled)
Closed mixing of resin	
Fibres chopped in spray gun	
Resin applied by uncontrolled spray	Resin applied by controlled spray
Roller consolidation	
Room temperature cure	Oven cure
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent

Vacuum Bag Moulding

Vacuum bag moulding has been considered both as an extension to hand lay-up for increased consolidation, as well as a route for moulding co-mingled and prepreg materials. In this process a vacuum bag is placed over the uncured laminate and a vacuum drawn with the use of a pump, the laminate being held under vacuum during room temperature or oven cure. This process can be used to make the 1m^2 double curvature panel and the 1m x 8m sandwich panel case studies.

When a fibre and wet matrix are used, the impacts for the impregnation stage are the same as for hand lay-up, but the addition of vacuum bag consumables contributes 7% to the overall process. All the trends concerning the resin and fibre choice, preparation and application for vacuum bag moulding are also the same as those for hand lay-up.

The vacuum bagging process is also used to process co-mingled and prepreg materials. Compared to using glass/polyester for the 1m^2 double curvature panel, a reduction in environmental impact of 52% is achievable when using co-mingled glass/polypropylene, 33% for glass/epoxy prepreg and 2% for carbon/epoxy prepreg. However for the 1m x 8m sandwich panel the structural qualities of the carbon/epoxy prepreg allow a smaller quantity of material to be used, giving a 56% reduction in impact over glass/polyester (comparable to both the co-mingled glass/polypropylene and glass/epoxy prepreg).

The manufacturing route for the prepreg is also important, as the impact of a solvent-impregnated prepreg is 12% higher than a hot melt prepreg.

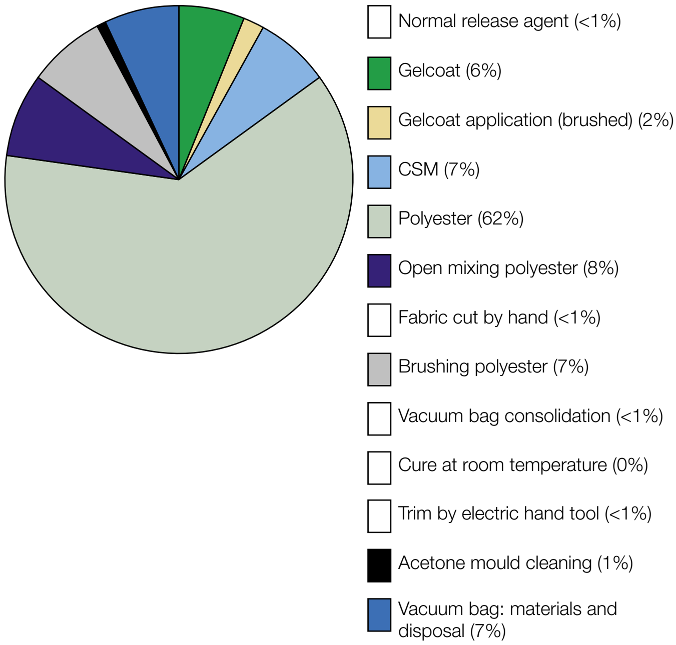


Figure 26: Breakdown of impacts for the basic vacuum bag moulding process for making the 1m^2 double curvature component

Vacuum bag moulding	
Base case process	**Other options modelled**
Polyester Resin (80% volume fraction)	Low styrene polyester resin Epoxy resin (hand lay-up and prepreg) Polypropylene (co-mingled)
No filler	15%, 30% and 50% ATH filler 15%, 30% and 50% $CaCO_3$ filler
Chopped strand mat (20% volume fraction)	Woven glass mat (hand lay-up and prepreg) Hemp (with polyester resin) Glass roving (co-mingled Carbon fibre (prepreg)
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Normal mould release	Eco mould release
Gelcoat	No gelcoat
Gelcoat applied by brush	Rolled gelcoat Sprayed gelcoat (controlled and uncontrolled)
Open mixing of resin	Closed mixing of resin
Fabric cut by hand	Mechanically cut fabric
Resin applied by brush	
Vacuum bag consolidation	
Room temperature cure	Oven cure
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent
Disposal of vacuum bag consumables	

Resin Infusion

In resin infusion, a vacuum is used to draw resin through dry fabrics under a vacuum bag. Once the resin has wetted out the fabric, the laminate is cured either at room temperature or in an oven. This process can be used to make the 1m^2 double curvature panel and the 1m x 8m sandwich panel case studies.

The largest impacts arise from the matrix, fibre and gelcoat, but the vacuum bag and infusion pipes also have a significant contribution. The process can be improved by using closed mixing of the resin (8% improvement), low styrene polyester (4% improvement) or epoxy resin (22% improvement).

Changing the fibre from woven glass to hemp increases the environmental impact by 6% for the 1m^2 double curvature panel.

However for the 1m x 8m sandwich panel, where the structural qualities of the woven glass are better utilised, changing to the hemp has an increased impact of 37% due to the higher quantities of materials needed. An increase in environmental impact of 3% is incurred when the gelcoat is sprayed (uncontrolled) instead of being brushed.

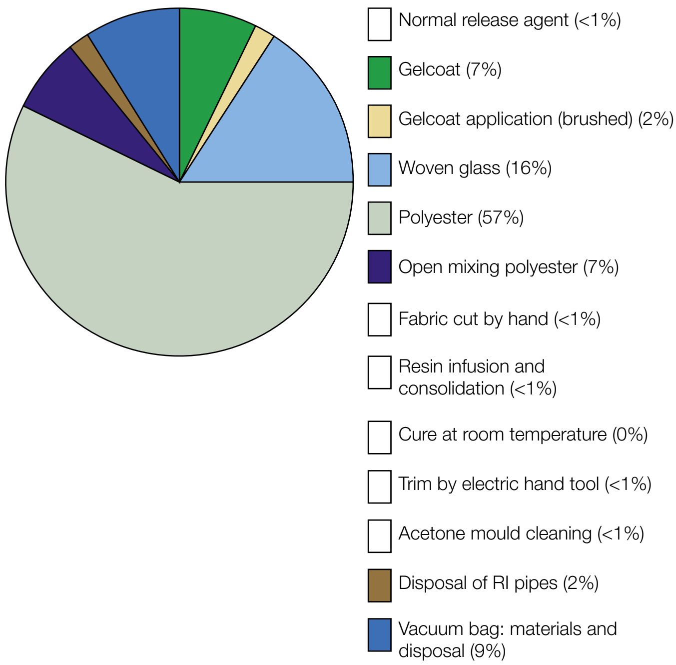


Figure 27: Breakdown of impacts for the basic resin infusion process for making the 1m^2 double curvature component

Resin Infusion	
Base case process	**Other options modelled**
Polyester Resin (68% volume fraction)	Low styrene polyester resin Epoxy resin
No filler	15%, 30% and 50% ATH filler 15%, 30% and 50% $CaCO_3$ filler
Woven glass mat (32% volume fraction)	Hemp (with polyester resin)
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Normal mould release	Eco mould release
Gelcoat	No gelcoat
Gelcoat applied by brush	Rolled gelcoat Sprayed gelcoat (controlled and uncontrolled)
Open mixing of resin	Closed mixing of resin
Fabric cut by hand	Mechanically cut fabric
Resin applied by vacuum infusion	
Vacuum bag consolidation	
Room temperature cure	Oven cure Cure in a heated mould
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent
Disposal of the vacuum bag materials and resin infusion pipes	

Resin Transfer Moulding

In resin transfer moulding, pressure and vacuum is used to force resin through dry fabrics in a matched mould. Once fully wetted the laminate is cured either at room temperature or in an oven. This process can be used to make the 1m^2 double curvature panel, the 1m x 8m sandwich panel and the complex component case studies, and it has been assumed that the higher pressure in resin transfer moulding will allow a higher fibre volume fraction than resin infusion.

Large environmental impacts arise from both the resin and the fibre, so large environmental improvements can be found by changing both of these materials. As before, improvements can be made by using filled polyesters (21% improvement for 50% $CaCO_3$ for the 1m^2 double curvature panel).

Changing from woven glass to hemp shows an improvement of 13% for the 1m^2 double curvature panel, 2% for the 1m x 8m sandwich panel and 22% for the complex component, whilst changing to carbon increases the environmental impact by 35% for the 1m^2 component and 91% for the complex component. However, where the structural qualities of carbon are better utilised, as in the 1m x 8m component, changing to carbon from woven glass decreases the environmental impact by 20%.

The only other variable that has a significant impact is the method of gelcoat application. Uncontrolled spraying of the gelcoat raises the overall environmental impact by 3% compared with applying the gelcoat by brush.

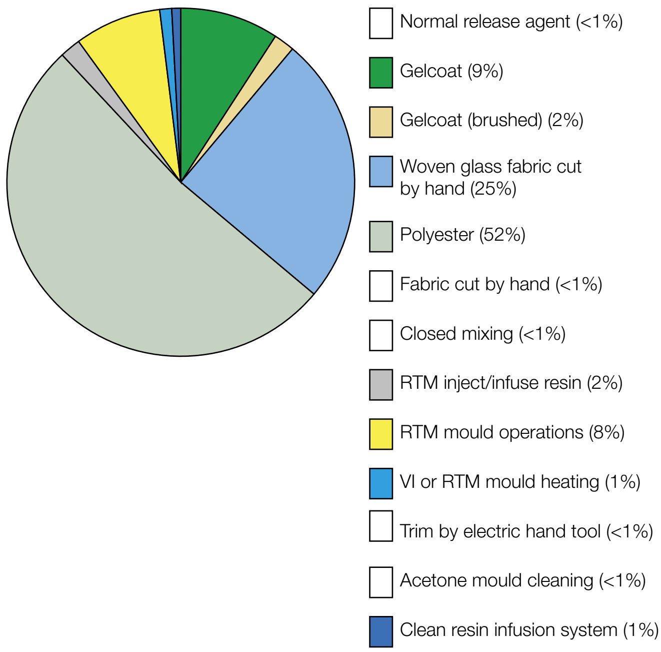


Figure 28: Breakdown of impacts for the resin transfer moulding base process for making the 1m^2 double curvature component

Resin Transfer Moulding	
Base case process	**Other options modelled**
Polyester Resin (55% volume fraction)	Low styrene polyester resin Epoxy resin
No filler	15%, 30% and 50% ATH filler 15%, 30% and 50% $CaCO_3$ filler
Woven glass mat (45% volume fraction)	Hemp (with polyester resin) Carbon
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Normal mould release	Eco mould release
Gelcoat	No gelcoat
Gelcoat applied by brush	Rolled gelcoat Sprayed gelcoat (controlled and uncontrolled)
Closed mixing of resin	
Fabric cut by hand	Mechanically cut fabric
Resin injected under pressure	
In-mould consolidation	
Cure in a heated mould	Room temperature cure
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent
RTM equipment cleaned with acetone flush	

Autoclave Moulding

Prepreg materials are commonly autoclave cured, a process in which the prepreg is consolidated at temperature under pressure and vacuum. This process can be used to make the 1m² double curvature panel, the 1m x 8m sandwich panel and the complex component case studies.

The environmental impacts for autoclave moulding arise from the prepreg and vacuum bag materials. The material choice is the only option that can significantly affect the total environmental impact with the carbon/epoxy prepreg having a large increase in impact (54% for the 1m² panel and 114% for the complex component compared to a glass/epoxy prepreg).

By contrast, using a carbon/epoxy prepreg for the 1m x 8m sandwich panel, achieves a reduction in environmental impact of 7%.

With consideration to the manufacturing method of a prepreg, a solution impregnation technique increases the impact of the base case process by 13% compared to a hot melt method.

No other variables were found to significantly affect environmental performance.

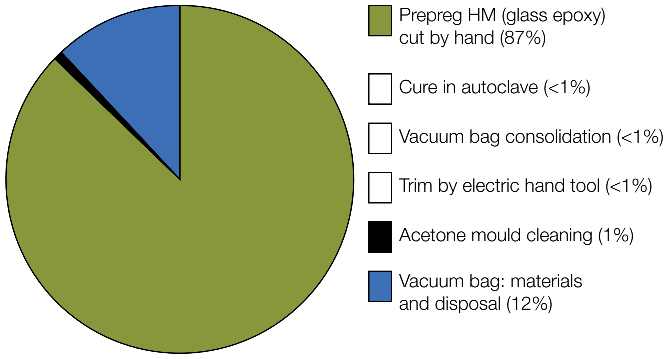


Figure 29: Breakdown of impacts for the autoclave moulding base process for making the 1m² double curvature component

Autoclave moulding	
Base case process	**Other options modelled**
Glass/epoxy prepreg (45% fibre volume fraction) (hot melt)	Carbon/epoxy prepreg (40% fibre volume fraction) Solution impregnation
No core	PVC (for 1m x 8m sandwich panel) Balsa (for 1m x 8m sandwich panel)
Prepreg cut by hand	Mechanically cut prepreg
Vacuum bag consolidation	
Autoclave cure	
Trimming by electric hand tool	Trimming by CNC machine Trimming by hand
No post cure	Oven post cure
Mould cleaned with acetone	Mould cleaned with toluene/butanone cleaning agent
Disposal of vacuum bag consumables	

Pultrusion

Pultrusion is a continuous process for making constant cross-section profiles. Fibres and fabrics are continuously pulled through a resin bath and into a heated shaped die in which the resin cures to form the shape of the profile. This process can be used to make the 1m x 8m panel case study, modelled with ribs instead of the core material used in other processes.

The main environmental impacts for pultrusion arise from the resin. The embodied impacts are as discussed in previous sections but the emissions from the resin bath are also large due to the high surface area of the resin bath. Whilst resin injection pultrusion systems may have a lower environmental impact, no assessment of this form of pultrusion has been made within this guide.

Polyesters with 50% $CaCO_3$ filler and 50% ATH filler have been modelled as the matrices used in pultrusion are usually highly filled. The $CaCO_3$ resin performs better than the ATH (as described in Part 3), although the emissions from resin application are the same for both. The only other process option that can be changed, closed mixing, results in an 8% improvement of environmental impact for the process.

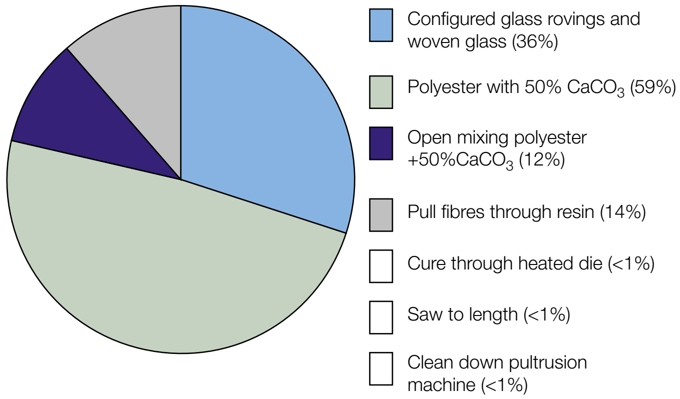


Figure 30: Breakdown of impacts for the pultrusion base process for making the 1m^2 double curvature component

Pultrusion	
Base case process	**Other options modelled**
Polyester Resin (60% volume fraction)	
50% $CaCO_3$ filler	50% ATH filler
Woven glass mat and glass rovings (40% volume fraction)	
Open mixing of resin	Closed mixing of resin
Resin applied by resin bath	
Consolidation through die	
Cure in heated die	
Cut to length by saw	
Equipment cleaned	

Compression Moulding

Compression moulding is used for both thermosetting and thermoplastic matrices. Material is placed in the lower cavity of a matched tool, the two halves of the tool are brought together and pressure applied to force the material to fill the cavity. In thermoplastic moulding the material is preheated and placed in a warm mould. By contrast, for thermosetting matrices the material is placed into a hot mould and cured under heat. This process can be used to make the 1m^2 double curvature panel and the complex component.

The environmental impacts in compression moulding arise mainly from the materials used. However, considerable impacts can also be attributed to the energy used in the moulding operation, and for SMC the energy used in mould heating. Mould heating for thermoplastics is very low (cool mould) and the pre-heat of the materials occurs in an IR oven which has relatively low energy requirements. An impact specific to PP/PP is the large wastage which can occur due to the quantity of excess material needed to secure it within the mould.

Large improvements can be achieved through material choice. All of the thermoplastic materials show an improvement over the SMC. Eg, by changing from the base case SMC to PP/PP, GMT or LFT, improvements 40%, 37% and 40% respectively are possible.

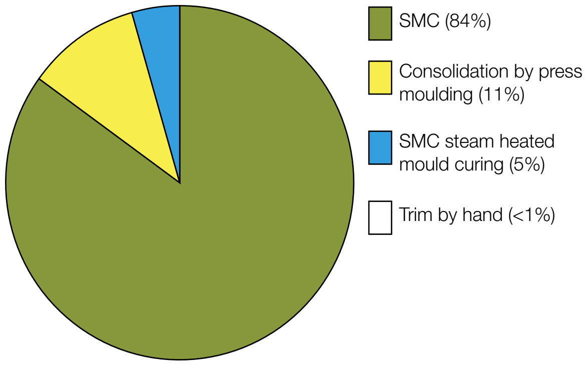


Figure 31: Breakdown of impacts for the compression moulding base process for making the 1m^2 double curvature component

Compression Moulding	
Base case process	**Other options modelled**
SMC	LFT PP/PP GMT
Material cut by hand (SMC)	Material cut mechanically (PP/PP, GMT, LFT)
Consolidation by press moulding	
No preheat	Pre heat in IR oven (PP/PP, GMT)
Cure in heated mould	Form in warm mould (PP/PP, GMT, LFT)
Trim by hand (not PP/PP)	Trim by CNC machine Trim by electric hand tool (PP/PP)

part 5:green guide ratings

Introduction

This part contains the final Green Guide ratings for complete composite processes. Three sections consider each product type in turn and tabular data is provided for each containing A to E ratings that compare each process.

These tables are intended as a reference for a broad range of composite products. Many of the environmental performance trends already discussed in this guide can be seen within these tables and therefore no further commentary on the results is provided.

The product types were chosen in an attempt to cover the broad range of composite types:

- A double curvature panel – this has a surface area of $1m^2$ with a panel stiffness equivalent to a 4mm thick chopped strand mat laminate.
- A flat sandwich panel – measuring 8m by 1m with a 25mm thick core, having a panel bending stiffness equivalent to a sandwich panel with a 4mm thick chopped strand mat skin.
- A complex moulded component – with a volume of $770cm^3$.

When modelling these products, care has been taken to ensure that composites produced within each product type have identical structural and performance characteristics.

Comparisons are only possible within each product type, and it is not possible to compare the ratings between products.

It is possible in this section to compare environmental and social trends for all the main material and process combinations on one page. A to E ratings are shown for each environmental category, along with a summary environmental rating, with an A rating for the lower environmental impacts.

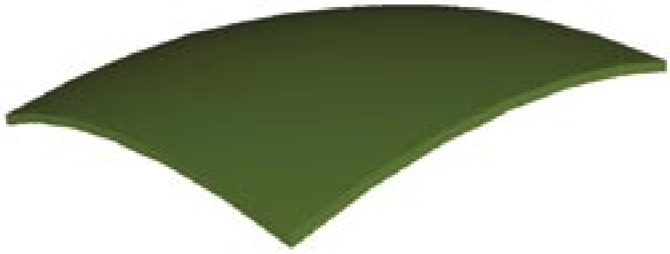
Two A to E social ratings are also given, for risk and remuneration, with an A rating showing a lower level of risk or higher remuneration for the operator.

For each product type the base case processes are listed first in each table, allowing a quick and easy comparison between the main different processes. These rows are followed by sub-sections on each of the main processes relevant to that product, to allow direct detailed comparisons of materials and process options.

It is important to note that this Green Guide rates products on a scale of A to E to provide a more detailed categorisation than the A to C ratings in previous BRE Green Guides. Differences also exist between guides because of variation in product types and study periods. For this reason, comparisons with results in other Green Guides should not be made.

Double-Curvature Panel 1m²

A generic component with a surface area of 1m² and a panel stiffness equivalent to a 4mm thick chopped strand mat laminate. This was selected as being typical of applications as diverse as automotive panels and architectural cladding.



Process	Material Choice	Environmental Indicators												Social Indicators	
		Summary Environmental Rating	Climate Change	Fossil Fuel Depletion	Ozone	Human Toxicity	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Risk Score	Remuneration
Hand Lay-Up	CSM/Polyester	**E**	B	C	A	E	C	A	A	D	A	E	B	D	E
Spray-up	Glass rovings/Polyester	**E**	B	C	A	E	B	A	B	D	A	D	B	D	E
Vacuum Bag Moulding	CSM/Polyester	**E**	B	C	A	E	C	A	A	D	A	E	B	D	E
RTM	Woven Glass/Polyester	**C**	C	C	A	C	E	A	B	B	A	A	D	C	E
Resin Infusion	Woven Glass/Polyester	**D**	B	C	A	D	D	A	B	C	A	B	C	C	C
Autoclave Moulding	Glass/Epoxy Prepreg	**B**	C	B	A	A	E	C	B	C	B	A	D	B	B
Compression Moulding	SMC	**C**	B	C	A	D	A	A	B	C	A	A	C	B	B
Hand Lay-Up	CSM/Polyester	**E**	B	C	A	E	C	A	A	D	A	E	B	D	E
	Woven Glass/Polyester	**D**	B	B	A	D	C	A	A	C	A	D	C	C	E
	Hemp/Polyester	**D**	B	B	A	E	A	A	A	C	A	D	A	C	E
	CSM/Polyester +50% $CaCO_3$ filler	**B**	A	A	A	C	C	A	A	B	A	D	D	D	E
	CSM/Polyester +50% ATH filler	**C**	B	B	A	C	D	A	B	E	A	D	E	D	E
	CSM/Low styrene (LS) polyester	**D**	B	C	A	E	C	A	A	D	A	C	B	D	E
	CSM/LS polyester +50% $CaCO_3$ filler	**B**	A	A	A	C	C	A	A	B	A	C	D	D	E
	CSM/LS polyester +50% ATH filler	**C**	B	B	A	C	D	A	B	E	A	C	E	D	E
	CSM/Epoxy	**C**	C	A	A	B	C	E	C	E	C	A	C	D	E
	Hemp/LS polyester +50% $CaCO_3$ filler	**B**	A	A	A	C	A	A	A	B	A	D	B	D	E
Spray-up	Glass rovings/Polyester	**E**	B	C	A	E	B	A	B	D	A	D	B	D	E
	Glass rovings/Polyester +50% $CaCO_3$ filler	**C**	B	B	A	C	B	A	A	B	A	D	D	E	E
	Glass rovings/Polyester +50% ATH filler	**C**	B	B	A	C	D	A	B	E	A	D	E	D	E
	Glass rovings/Low styrene (LS) polyester	**D**	B	C	A	E	B	A	B	D	A	C	B	D	E
	Glass rovings/LS polyester +50% $CaCO_3$filler	**B**	B	B	A	C	B	A	A	B	A	C	D	E	E
	Glass rovings/LS polyester +50% ATH filler	**C**	B	B	A	C	D	A	B	E	A	C	E	D	E
Vacuum Bag Moulding	CSM/Polyester	**E**	B	C	A	E	C	A	A	D	A	E	B	D	E
	Glass/Epoxy Prepreg (hot melt)	**C**	C	B	A	B	E	D	B	D	B	A	D	C	A
	Carbon/Epoxy Prepreg (hot melt)	**E**	E	E	E	C	A	B	E	B	E	A	B	B	A
	Co-mingled glass/Polypropylene	**A**	B	B	A	B	A	A	B	B	A	A	B	C	A

Continued . . .

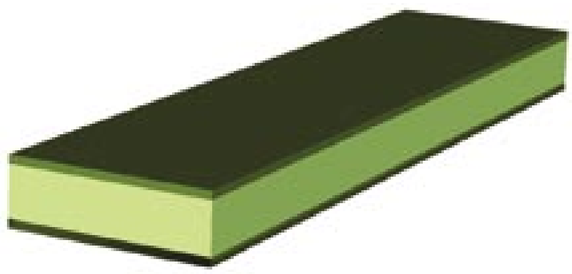
Process	Material Choice	Environmental Indicators												Social Indicators	
		Summary Environmental Rating	Climate Change	Fossil Fuel Depletion	Ozone	Human Toxicity	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Risk Score	Remuneration
RTM	Woven Glass/Polyester	**C**	C	C	A	C	E	A	B	B	A	A	D	C	E
	Hemp/Polyester	**B**	B	B	A	D	A	A	B	B	A	A	A	C	E
	Carbon/Polyester	**D**	D	E	E	D	A	A	E	B	D	A	A	C	E
	Woven Glass/Polyester +50% $CaCO_3$ filler	**B**	B	B	A	B	E	A	B	A	A	A	E	D	E
	Woven Glass/Polyester +50% ATH filler	**B**	C	B	A	B	E	A	C	C	A	A	E	C	E
Resin Infusion	Woven Glass/Polyester	**D**	B	C	A	D	D	A	B	C	A	B	C	C	C
	Hemp/Polyester	**D**	B	C	A	E	A	A	A	D	A	C	A	C	C
	Woven Glass/Low styrene (LS) polyester	**C**	B	C	A	D	D	A	B	C	A	B	C	C	C
	Woven Glass/Epoxy	**B**	C	A	A	A	E	D	C	C	B	A	D	C	C
Autoclave Moulding	Glass/Epoxy Prepreg (hot melt)	**B**	C	B	A	A	E	C	B	C	B	A	D	B	A
	Carbon/Epoxy Prepreg (hot melt)	**D**	D	E	E	B	A	B	E	B	E	A	B	B	A
Compression Moulding	SMC	**C**	B	C	A	D	A	A	B	C	A	A	C	B	D
	PP/PP	**A**	B	B	A	A	A	A	C	B	A	A	A	A	D
	GMT	**A**	B	B	A	A	B	A	C	B	A	A	B	A	D
	LFT	**A**	B	B	A	A	B	A	C	A	A	A	B	A	D

All the processes modelled in this study can be used to manufacture this component except for pultrusion because this component is not of constant cross-section.

From looking at the base cases where the material is a standard polyester/glass combination it can be seen that the closed mould processes (RTM and resin infusion) perform better environmentally than open mould processes (hand lay-up, vacuum bagging and spray-up).

Flat Sandwich Panel 1m x 8m

A generic component measuring 1m x 8m with a 25mm thick core, having a panel bending stiffness equivalent to a sandwich panel with a 4mm thick chopped strand mat skin. For the pultrusion process the component is modelled with ribs instead of the core material used in other processes. This component is designed to be representative of large-scale applications such as bridge decks and marine structures.



Process	Material Choice	Environmental Indicators												Social Indicators	
		Summary Environmental Rating	Climate Change	Fossil Fuel Depletion	Ozone	Human Toxicity	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Risk Score	Remuneration
Vacuum Bag Moulding	CSM/Polyester	**E**	C	E	A	E	D	A	B	D	A	E	B	C	E
RTM	Woven Glass/Polyester	**B**	C	C	A	B	E	A	B	B	A	A	C	B	E
Resin Infusion	Woven Glass/Polyester	**C**	B	C	A	C	D	A	B	C	A	B	C	B	C
Autoclave Moulding	Glass/Epoxy Prepreg (hot melt)	**A**	B	A	A	A	D	B	B	C	B	A	C	A	B
Pultrusion	Woven glass and glass rovings/Polyester +$CaCO_3$ filler	**A**	A	A	A	B	B	A	A	A	A	C	C	B	A
Hand Lay-Up	CSM/Polyester	**E**	C	E	A	E	D	A	B	D	A	E	C	C	E
	Woven Glass/Polyester	**C**	B	C	A	C	D	A	B	C	A	C	C	B	E
	Hemp/Polyester	**E**	B	D	A	E	A	A	B	D	B	E	A	C	E
	CSM/Polyester +50% $CaCO_3$ filler	**C**	A	B	A	C	D	A	A	B	A	D	E	D	E
	CSM/Polyester +50% ATH filler	**D**	B	C	B	C	E	A	C	E	A	D	E	D	E
	CSM/Low styrene (LS) polyester	**E**	C	E	A	E	D	A	B	D	A	C	C	C	E
	CSM/LS polyester +50% $CaCO_3$ filler	**B**	A	B	A	C	D	A	A	B	A	C	E	D	E
	CSM/LS polyester +50% ATH filler	**C**	B	C	B	C	E	A	C	E	A	C	E	D	E
	Woven Glass/Epoxy	**B**	C	A	A	A	E	C	C	C	C	A	C	B	E
	CSM/Epoxy	**C**	E	B	A	B	E	E	E	E	E	A	D	C	E
	Woven Glass/LS polyester +50% $CaCO_3$ filler	**A**	A	A	A	B	D	A	A	B	A	B	D	C	E
Vacuum Bag Moulding	CSM/Polyester	**E**	C	E	A	E	D	A	B	D	A	E	B	C	E
	Glass/Epoxy Prepreg	**A**	B	A	A	A	D	B	B	C	B	A	C	A	A
	Carbon/Epoxy Prepreg	**A**	B	B	E	A	A	A	C	B	C	A	A	A	A
	Co-mingled glass/Polypropylene	**A**	A	B	A	B	A	A	B	B	A	A	B	B	A
Spray-up	Glass rovings/Polyester	**E**	C	E	A	E	C	A	C	D	A	D	B	C	E
	Glass rovings/Polyester+50% ATH filler	**D**	C	D	B	C	E	A	D	E	B	C	E	D	E
	Glass rovings/Polyester+50% $CaCO_3$ filler	**C**	B	C	A	C	C	A	B	B	A	D	D	D	E
	Glass rovings/Low styrene (LS) polyester	**E**	C	E	A	E	C	A	C	D	A	C	B	C	E
	Glass rovings/LS polyester +50% ATH filler	**C**	C	D	B	C	E	A	D	E	B	B	E	D	E
	Glass rovings/LS polyester +50% $CaCO_3$ filler	**C**	B	C	A	C	C	A	B	B	A	B	D	D	E

Continued . . .

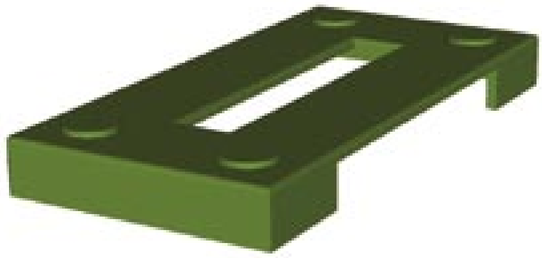
Process	Material Choice	Environmental Indicators												Social Indicators	
		Summary Environmental Rating	Climate Change	Fossil Fuel Depletion	Ozone	Human Toxicity	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Risk Score	Remuneration
RTM	Woven Glass/Polyester	**B**	C	C	A	B	E	A	B	B	A	A	C	B	E
	Hemp/Polyester	**B**	B	B	A	C	A	A	B	C	B	A	A	B	E
	Carbon/Polyester	**A**	B	C	E	B	A	A	C	A	C	A	A	A	E
	Woven Glass/Polyester +50% ATH filler	**A**	B	B	A	B	E	A	B	B	A	A	D	B	E
	Woven Glass/Polyester +50% $CaCO_3$ filler	**B**	C	B	A	B	E	A	C	B	A	A	E	B	E
	Carbon/Polyester +50% $CaCO_3$ filler	**A**	A	B	E	A	A	A	C	A	C	A	A	A	E
Resin Infusion	Woven Glass/Polyester	**C**	B	C	A	C	D	A	B	C	A	B	C	B	C
	Polyester/Hemp	**D**	C	D	A	E	A	A	B	D	B	C	A	C	C
	Low styrene polyester/Woven Glass	**C**	B	C	A	C	D	A	B	C	A	A	C	B	C
	Low styrene polyester/Hemp	**D**	C	D	A	E	A	A	B	D	B	B	A	C	C
	Woven Glass/Epoxy	**B**	C	A	A	A	E	C	C	C	C	A	D	B	C
Autoclave Moulding	Glass/Epoxy Prepreg (Hot melt)	**A**	B	A	A	A	D	B	B	C	B	A	C	A	B
	Carbon/Epoxy Prepreg (Hot melt)	**A**	B	B	E	A	A	A	C	A	C	A	A	A	B
Pultrusion	Woven glass and glass rovings/Polyester+ $CaCO_3$ filler	**A**	A	A	A	A	C	A	A	A	A	B	C	B	A
	Woven glass and glass rovings/Polyester+ ATH filler	**A**	A	A	A	A	D	A	A	B	A	B	D	B	A

All processes are modelled except compression moulding as the component is too large for this process.

A similar trend can be seen as for the double curvature panel, with the open mould processes performing worse. Because the sandwich panel is thicker than the double-curvature flat panel, lower amounts of higher performance fabrics are needed to give equivalent bending stiffness to a 4mm thick chopped strand mat laminate. These materials therefore show improved impact results compared to those for the double curvature panel.

Complex Moulded Component

A complex moulded component, modelled as having a fixed volume of 770cm^3, where the other components have been modelled as having a fixed panel bending stiffness. This component has been selected as being typical of a part with more features and complexity (eg ribs and bosses) that can typically be manufactured using an open mould process.



Process	Material Choice	Environmental Indicators												Social Indicators	
		Summary Environmental Rating	Climate Change	Fossil Fuel Depletion	Ozone	Human Toxicity	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Risk score	Remuneration
RTM	Woven Glass/Polyester	**B**	B	B	A	C	E	A	A	C	A	C	D	D	E
Autoclave Moulding	Glass/Epoxy Prepreg (hot melt)	**B**	B	A	A	A	D	E	B	E	A	A	D	B	B
Compression Moulding	SMC	**B**	A	B	A	D	A	A	A	C	A	B	C	C	D
RTM	Woven Glass/Polyester	**B**	B	B	A	C	E	A	A	C	A	C	D	D	E
	Hemp/Polyester	**B**	A	A	A	C	B	A	A	C	A	C	A	C	E
	Carbon/Polyester	**E**	D	E	E	E	B	A	E	C	D	C	A	C	E
	Woven Glass/Polyester +50% ATH filler	**B**	B	B	A	B	E	A	A	D	A	B	E	D	E
	Woven Glass/Polyester +50% $CaCO_3$ filler	**B**	A	A	A	B	D	A	A	A	A	A	E	D	E
	Hemp/Polyester +50% $CaCO_3$ filler	**A**	A	A	A	B	A	A	A	A	A	A	B	C	E
Autoclave Moulding	Glass/Epoxy Prepreg (hot melt)	**B**	B	A	A	A	D	E	B	E	A	A	D	B	B
	Glass/Epoxy Prepreg (hot melt)	**E**	E	E	E	C	A	D	E	D	E	A	B	B	B
Compression Moulding	SMC	**B**	A	B	A	D	A	A	A	C	A	B	C	C	D
	PP/PP	**A**	A	A	A	A	A	A	A	A	A	A	A	B	D
	GMT	**A**	A	A	A	A	A	A	A	A	A	A	A	B	D
	LFT	**A**	A	A	A	A	B	A	A	A	A	A	B	B	D

The only processes that can make the complex moulded component are RTM, autoclave moulding and compression moulding.

It should be noted that because this component has been modelled as having a fixed volume, it is not possible to reduce quantities of materials used by using materials with better structural qualities. Thus materials of low environmental impact by volume (hemp and filled polyesters) perform well for this component and materials of high environmental impact, in particular carbon, perform badly for this component.

glossary

ATH	Alumina Trihydrate
BRE	Building Research Establishment
CFC	Chlorofluorocarbons
CNC	Computer Numerically Controlled
CSM	Chopped Strand Mat
GMT	Glass Mat Thermoplastic
HCFC	Hydro Chlorofluorocarbons
LCA	Life Cycle Assessment
LFT	Long Fibre Thermoplastic
MEKP	Methyl Ethyl Ketone Peroxide
NGCC	Network Group for Composites in Construction
PP	Polypropylene
PPE	Personal Protective Equipment
Prepreg	Pre-Impregnated Fibre
PVA	Poly Vinyl Acetate
PVC	Poly Vinyl Chloride
RTM	Resin Transfer Moulding
SMC	Sheet Moulding Compound
UV	Ultraviolet
VOCs	Volatile Organic Compounds

green guide to composites

an environmental profiling system for composite materials and products

This guide has been created to allow the composites industry to understand the environmental and social impacts of different composite materials and manufacturing processes. The life-cycle impacts of each material and process choice from the cradle to the factory gate are presented in simple A to E comparative rankings, for the first time allowing informed decisions to be made on the environmental and social effects of composite materials and process choices.